Atomic Energy Control Board
P.O. Box 1046
Ottawa, Canada
K1P 5S9

Commission de contrôle de l'énergie atomique
C.P. 1046
Ottawa, Canada
K1P 5S9

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SEISMIC QUALIFICATION OF EQUIPMENT - A Summary of Findings

by

A.C. Heidebrecht
and W.K. Tso

Department of Civil Engineering
and Engineering Mechanics
McMaster University
Hamilton, Ontario

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SEISMIC QUALIFICATION OF EQUIPMENT

ABSTRACT

This report describes the results of an investigation into the seismic qualification of equipment located in CANDU nuclear power plants. It is particularly concerned with the evaluation of current seismic qualification requirements, the development of a suitable methodology for the seismic qualification of safety systems, and the evaluation of seismic qualification analysis and testing procedures.

A fault tree study, with a logic diagram formulation, is used to establish that the plant as a whole will be seismically qualified provided that each of the safety systems is qualified. A distinction is drawn between the qualification of a single piece of equipment or component and that of a complete safety system. This leads to the development of a methodology for the qualification of safety systems, which includes such additional requirements as location and interface qualification.

The evaluation of current seismic qualification procedures includes both analysis and testing procedures and a comparison of the two approaches. Procedures for combined analysis and testing are also evaluated. This is followed by a detailed investigation of testing procedures which includes seismic floor motion characteristics, single frequency test procedures and the actual testing of an instrument cabinet using multi-frequency time-history procedures.

RÉSUMÉ

Le présent rapport fait état des résultats d'une recherche portant sur l'homologation de l'équipement des centrales nucléaires CANDU en matière de résistance aux séismes. Il traite surtout de l'évaluation des exigences actuelles d'homologation en cas de séismes, de la mise au point d'une méthode appropriée permettant d'homologuer des systèmes de sûreté, et de l'évaluation des procédures d'analyse et d'essais d'homologation.

Une étude menée à l'aide d'un arbre de défaillances, grâce à sa formulation par diagramme logique, permet de prévoir que l'ensemble de la centrale pourra résister aux séismes dans la mesure où chacun des systèmes de sûreté sera homologué. En outre, en distinguant entre l'homologation d'une pièce détachée ou d'un composant de l'équipement et celle d'un système complet de sûreté, on en arrive à l'élaboration d'une méthode permettant d'homologuer des systèmes de sûreté qui tient compte d'exigences additionnelles reliées à l'emplacement et à l'agencement des pièces.

L'évaluation des procédures actuelles d'homologation comprend l'étude des procédures d'analyse et d'essai, ainsi que la comparaison de ces deux approches. Elle traite également des procédures d'analyse et d'essai conjoints, puis d'une analyse détaillée de différentes procédures d'essai.

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NOTATION

a	=	acceleration time history
CRF	=	cumulative RMS function
n	=	total number of cycles
N_{EQ}	=	equivalent number of cycles of cumulative damage
R_i	=	amplitude of cycle "i"
R_p	=	maximum amplitude
t	=	time
β	=	cumulative damage process parameter related to material properties and test conditions

1. INTRODUCTION

1.1 Basic Seismic Qualification Requirements

The potential occurrence of an earthquake is one of the natural hazards which has to be taken into account in the design and construction of a nuclear power plant. The extent of protection which should be provided to any part of the plant is primarily affected by nuclear safety considerations, i.e. that the effects of earthquakes do not lead to unacceptable releases of radioactive materials to the public.

The effects of an earthquake at a nuclear power plant are expressed in terms of ground motion at the site, which is dependent upon the magnitude of the earthquake, the distance of the site from the earthquake epicentre and the soil conditions at the site. The intensity of ground motion used in the design of a nuclear power plant is related to the probability of the occurrence of earthquakes in the geographical area whose earthquakes affect the site.

In Canada, the seismic design requirements for nuclear power plants are expressed in terms of two levels of earthquake effects, namely the Design Basis Earthquake (DBE) and Site Design Earthquake (SDE). These two levels are defined in the following way [6]:

> DBE means an engineering representation of potentially severe effects at the site of earthquakes applicable to the site that have sufficiently low probability of being exceeded during the lifetime of the plant.
>
> SDE means an engineering representation of the effects at the site of a set of possible earthquakes with an occurrence rate, based on historical records, not greater than 0.01 per year.

In general all safety systems and other equipment and structures which are needed to safely shut down the reactor, control decay heat and control release of radioactivity are required to be designed to the DBE level. In addition, the emergency core cooling system and supporting systems must remain functional in the event of a loss of coolant accident (LOCA) which is followed by SDE level shaking. All systems,

structures and equipment within a nuclear power plant are classified into three levels of seismic qualification, i.e. i) qualified to DBE level, ii) qualified to SDE level, or iii) not seismically qualified.

For equipment which is required to be seismically qualified, there is a further categorization according to its functional requirements. Equipment which must maintain its pressure boundary and/or structural integrity during and/or following an earthquake is referred to as Category "A". Equipment which must maintain its mechanical and/or electrical safety related function, in addition to any pressure boundary integrity, is referred to as Category "B".

Consequently, the seismic qualification requirements for all equipment in a CANDU nuclear power plant are specified in terms of earthquake level (DBE or SDE) and design category (A or B). The requirements for a 600 MW single unit CANDU reactor, which were used in various phases of this investigation, are given in reference [10]. The methodology for determining the appropriate ground motion [7] and the subsequent design procedure [8] have recently been published as CSA Standards. A CSA Standard covering testing procedures [9] is in the process of development.

1.2 Purpose and Results of this Study

The objectives of the study described in this report were: (i) to provide an evaluation of the current seismic qualification requirements for equipment in the CANDU reactor system, (ii) to develop a methodology for the seismic qualification of CANDU safety systems and (iii) to evaluate seismic qualification analysis and testing procedures for the purpose of providing input in the formulation of Canadian seismic qualification standards.

The foregoing objectives are rather all-encompassing, but it is concluded that they have been achieved, given the scope of this particular investigation. The key findings are summarized in the following paragraphs.

In order to evaluate the current seismic qualification requirements, a fault tree study was used to develop a logic diagram which identified the various paths of failure necessary to result in public release of radioactivity following an earthquake. By comparing

the systems involved along each failure path with the AECL design requirements, it was found that the nuclear power plant as a whole would be seismically qualified if the specified AECL design requirements for each system were met.

Based on the foregoing, it is clear that the seismic safety adequacy of the overall nuclear power plant depends upon the adequacy of the seismic qualification of the different systems which are designed to ensure the safety of the plant. When evaluating "safety systems", it was determined that the seismic qualification of components or individual pieces of equipment within those systems is a necessary but insufficient condition to ensure the qualification of the overall safety system. The additional requirements, over and above component qualification, were then specified in terms of two additional types of qualification, namely location qualification and interface qualification. The methodology for these additional qualification types was illustrated by using the Shutdown System 2 (SDS2) at the Ontario Hydro Pickering B Station as an example.

In terms of component qualification, a critical evaluation of current seismic qualification procedures was included in this study. The two most common approaches are qualification by analysis and by testing, each of which has its advantages and drawbacks. The primary advantage of analysis is its inherent flexibility for use in qualifying a wide variety of equipment, irrespective of shape, size or weight. If carried out properly, analysis is a viable approach for ensuring the integrity of equipment after an earthquake. On the other hand, qualification by testing has the advantage of being able to demonstrate functionality in a direct manner. Testing is limited by the shaking capacity of available testing facilities and would not be suitable for equipment of large size and/or weight. The emphasis of the evaluation in this study was on the comparison of the two different approaches and on the comparison of methods and procedures within each approach. The advantages, drawbacks, limitations and uncertainties were provided in order that engineers could choose the most suitable approach and procedure for their particular requirements.

Because of the difficulty in comparing test procedures, these were subject to additional investigations. An important aspect of this study

was the development of a number of "new" parameters which would provide a more complete characterization of seismic floor motions. Single frequency testing procedures were evaluated using these characterization parameters with the result that the sine beat test was found to provide the best simulation (within the single frequency test procedures) of actual seismic floor motions. Multi-frequency test procedures were evaluated by testing an actual instrument cabinet. This testing demonstrated that the single enveloping of a design floor response spectrum in creating a test environment is insufficient to ensure that some other important features are simulated.

1.3 Scope of Report

The stages of this study which were outlined above are considered in more detail in the remainder of this report. Chapter 2 provides an abridged version of the fault tree study and describes how the overall qualification of a CANDU power plant is assured if the various safety systems are qualified. In Chapter 3, the methodology of the seismic qualification of a system is outlined and the application of this methodology to the SDS2 safety system is provided for illustrative purposes. Chapter 4 provides a broad outline of the evaluation of equipment system qualification approaches and procedures. The further investigation of testing procedures, including the experimental work on an instrument cabinet, is described in Chapter 5.

The overall results are summarized in Chapter 6. References [1] through [5] are reports which provide the details of the various phases of the overall study.

2. FAULT TREE STUDY

To develop a framework to classify equipment according to its safety significance in the event of an earthquake, it is necessary to understand the inter-relationship among different safety systems and their contribution to the overall safety of the nuclear power plant in the event of an earthquake. This is carried out in this study by the construction of a fault tree; a more detailed description of this study is given in reference [1].

A fault tree is an event logic diagram relating component failures to a particular system failure. The causes of an event are then indicated and connected to the main event by logic gates. In the present analysis, only two common logic gates are used. The "OR" gate indicates that the "output event" occurs if and only if at least one of the "input events" occurs. The "AND" gate indicates that the output event occurs if and only if all the input events occur.

The procedure outlined above is then repeated for each of the causes that serve as input events to the main event. It then applies to the causes of causes until all events have been fully developed. In the present study, events are considered fully developed when the causes have been shown to the independent system failure level.

2.1 Description of Fault Tree

The overall fault tree is shown in Fig. 2.1. In addition, for convenience in referencing the detailed discussion which follows, the various branches are also illustrated in Figs. 2.2 to 2.7.

The main purpose of construction of the fault tree is to serve as a display of results. If the design is adequate, the fault tree will show that all the conceivable causes have been included. If the design is inadequate, the fault tree will reveal the weak points. No attempt is made here to carry out a detailed analysis to assess the probability of occurrence of different events.

Only events that may arise due to the occurrence of an earthquake are included in the construction of the fault tree. In this sense, the fault tree developed is not complete; however, it is sufficient to clarify the safety significance of the various systems. Also, it should be pointed out that the 600 MW single unit design of the CANDU reactor

system has been used for this study. Some comments may not be applicable to other configurations of the CANDU system.

The main event in the fault tree is the Release of Radioactivity to the Public. This event may occur either due to leakage of radioactive material from the spent fuel bay area, or failure of the Main Reactor System. Release of radioactivity from the main reactor system may arise if all the following events occur. These events are: (i) Fuel Failure, (ii) Failure of Heat Removal System, and (iii) Loss of Containment.

2.2 Fuel Failures

The occurrence of any one of a number of events will lead to Fuel Failure, as illustrated in Fig. 2.3. These events are: (i) Failure in the Fuel Handling System, (ii) Loss of Reactor Power Control, (iii) Loss of Coolant Accident (LOCA) and Loss of Emergency Core Cooling (ECC), and (iv) LOCA and Loss of Moderator Cooling Capacity.

The Fuel Handling System may fail in either the connected state or in the unconnected state. If the fueling machine were connected to the core, such a failure could cause a small LOCA. Since only one channel is likely to be involved, the amount of heat produced, and hence the resulting pressure build-up, may cause a malfunction of the heat transport system, but it is unlikely that this will cause loss of containment. If the Fuel Handling System fails in the unconnected state, only the fueling machine and not the core will be involved. In this case, the failure will be less critical and results in some pressure build-up within the containment boundary of the plant.

Loss of Reactor Power Control is basically concerned with the loss of ability to control or shutdown the reactor core in case of emergency. Loss of Reactor Power Control occurs if all the following events occur: (i) Loss of Regulation (LOR), (ii) Failure of Shutdown System Number 1 (SDS1), and (iii) Failure of Shutdown System Number 2 (SDS2).

Loss of Regulation (LOR) may arise if either there is a failure in the Reactor Regulating System, or there is a failure in the Control Computer. Both the Reactor Regulating System and its associated Control Computer are process systems which also have safety functions. In case either of such systems fail, the shutdown function is taken over by the two special safety systems SDS1 and SDS2.

Shutdown System 1 (SDS1) consists of control rods which can be lowered into the reactor core to shutdown the reactor in case of emergency. Shutdown System 2 (SDS2) employs the injection of concentrated gadolinium nitrate solution to poison the core.

In addition to failure of the Fuel Handling System and loss of Reactor Power Control, a LOCA and a loss of Emergency Core Cooling (ECC) system would lead to Fuel Failure. Also, a LOCA and a failure of the Moderator Cooling System may also lead to Fuel Failure.

2.3 Loss of Heat Removal System

Any one of the three events listed below can lead to a loss of the Heat Removal System, as illustrated in Fig. 2.4. These events are (i) Spontaneous pipe break, (ii) Induced pipe break (LOCA), and (iii) Boiler failure due to structural damage.

In addition to pipe rupture as a result of structural failure, the event of induced pipe break can be a result of Power Mismatch. Power Mismatch is either a result of Loss of Circulation, or a Loss of Heat Sink (LOHS).

Loss of Circulation occurs as a result of pump failure and thermal siphoning failure, as shown in Fig. 2.5. Malfunctioning of the pumps may either be due to some mechanical failure of the pumps, or due to the lack of power to drive the pumps. Loss of Class IV power or Class V power would constitute a failure of power received to drive and control the pumps.

Loss of Heat Sink (LOHS) occurs as a result of loss of water flowing in the system, or loss of outflow of steam out of the system, as illustrated in Fig. 2.6. Loss of inflow of water results if (i) there is a loss of feedwater and auxiliary feedwater, and (ii) there is a loss of inventory water in the boiler or a malfunctioning of the Emergency Water System (EWS) or the Emergency Power System (EPS). Should the feedwater and auxiliary feedwater fail, the inflow of water can be made up using the inventory water in the boiler for the first 30 minutes of shutdown, provided that after 30 minutes, the EWS powered by EPS will be functioning to remove the decay heat. The loss of outflow of steam can be caused by the failure of the main steam safety valve, and the failure of the condenser in the balance of plant.

2.4 Loss of Containment

The third event that can lead to the release of radioactive material to the public is the Loss of Containment in the main power plant, which is shown in Fig. 2.7. By Loss of Containment, we imply a loss of containment boundary. This can occur either due to structural failure of the containment vessel, or the loss of containment appertenances. Structural failure may be due to direct damage from ground shaking, or failure of the dousing system to limit the rise in internal pressure of the containment vessel. Loss of containment appertenances occurs either when there is failure in the air lock, or failure of the ventilating valve, or the failure of a closed loop outside containment such as the vapour recovery system.

2.5 Required Seismic Qualification of Safety Related Systems

To ensure that the chance of public release of radioactivity will be remote after a large earthquake, it is necessary to ensure that the various base events in the fault tree become unlikely events after a large earthquake. In other words, the various systems which are involved in the base events need to be seismically qualified to ensure that they will not fail due to seismic excitation.

To specify seismic qualification for each system, it is necessary to specify both the earthquake level (DBE or SDE) and system category (A or B), as described in Section 1.1. The seismic classification of safety related systems and structures for the 600 MW single unit CANDU reactor is given by the AECL Design Guide DG-01343-2 [10] which contains a detailed listing of the various systems, their respective levels and categories, together with notes of explanation. A schematic diagram (taken from that Design Guide) showing the various systems and their seismic levels of qualification is given in Fig. 2.8.

Based on this Design Guide, the seismic resistance of the various systems identified in the construction of the fault tree can be assessed. The seismic qualification level and category which each system is required to satisfy is shown in brackets under each base event in Figs. 2.3 to 2.7. If a system is qualified for the DBE level of seismic excitation, its probability of failure following the occurence of a DBE will be very small. For convenience, it is assumed that

systems that are qualified for the DBE will survive (will not fail) after a DBE. On the other hand, systems which are qualified either to the SDE or a lower level of seismic excitation are assumed to have failed after the occurence of a DBE. With such simplifying assumptions, the safety significance of each system can be estimated by evaluating the consequence of its failure after a DBE.

Tracking from the base faults in the various branch of the fault tree, it can be shown [1] that the Fuel System, the Heat Removal System, and the Containment System are individually qualified for a DBE level event. Since the failure of all of them are required to lead to the Failure of the Main Reactor System, it follows that the Main Reactor System is qualified for a DBE. Observing that the Spent Fuel Bay is seismically qualified also up to the DBE level, one can logically conclude, from Fig. 2.2, that during the occurrence of a DBE, the likelihood of public release of radioactivity will be remote.

So far, it has been shown that with the various systems qualified to the DBE level, as specified by the AECL Design Guide DG-01343-2, the chance of public release of radioactivity from a CANDU plant after a DBE level earthquake will be very small. However, one should distinguish between system qualification and component qualification. As an example, the main heat transfer pump system is not qualified to the DBE level, even though the pumps themselves are qualified (see Fig. 2.5). The reason in this case is that the power sources which drive and control the pump respectively are not seismically qualified. The methodology involved for qualification of safety systems will be discussed in Chapter 3.

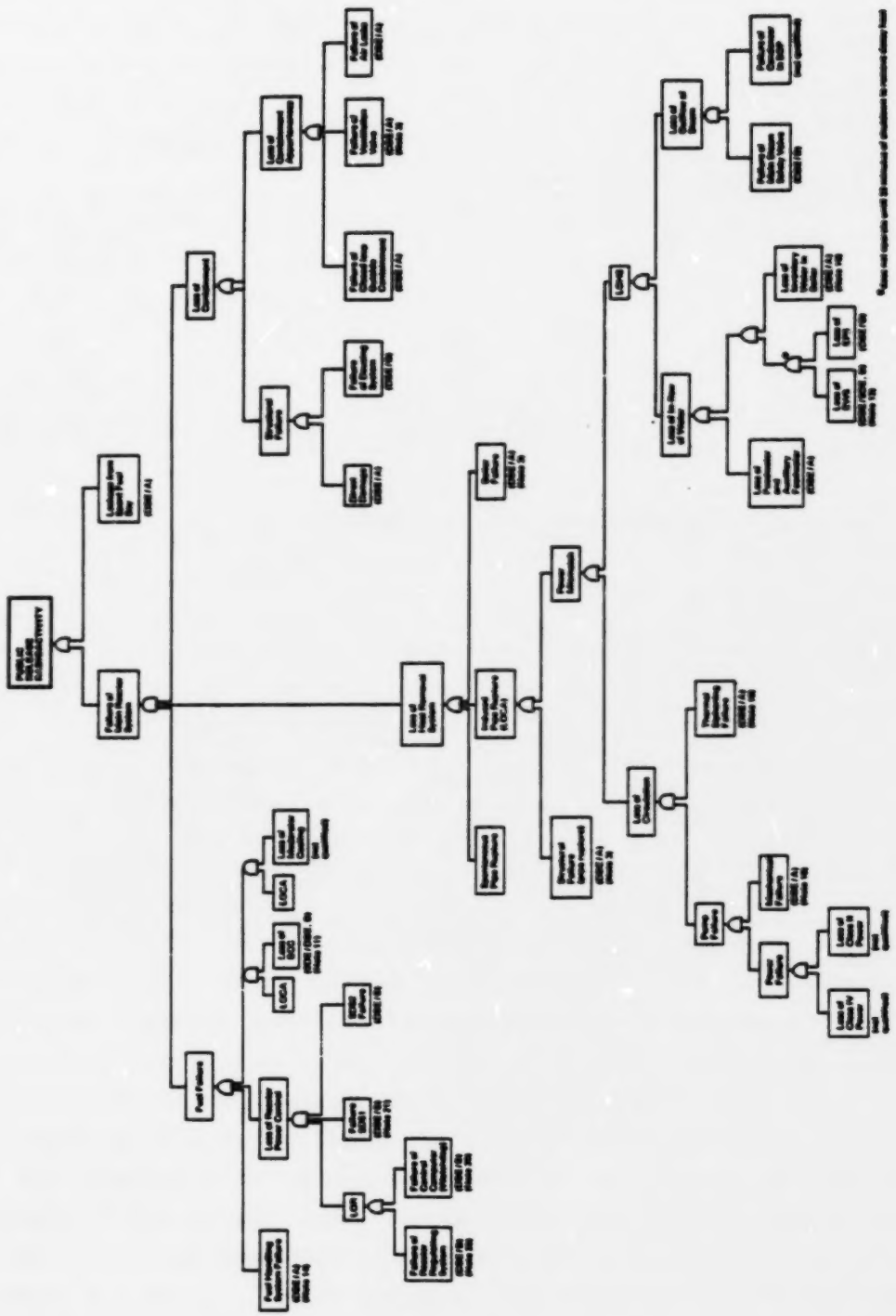


FIG. 2.1 OVERALL FAULT TREE RELATED TO SEISMIC SAFETY

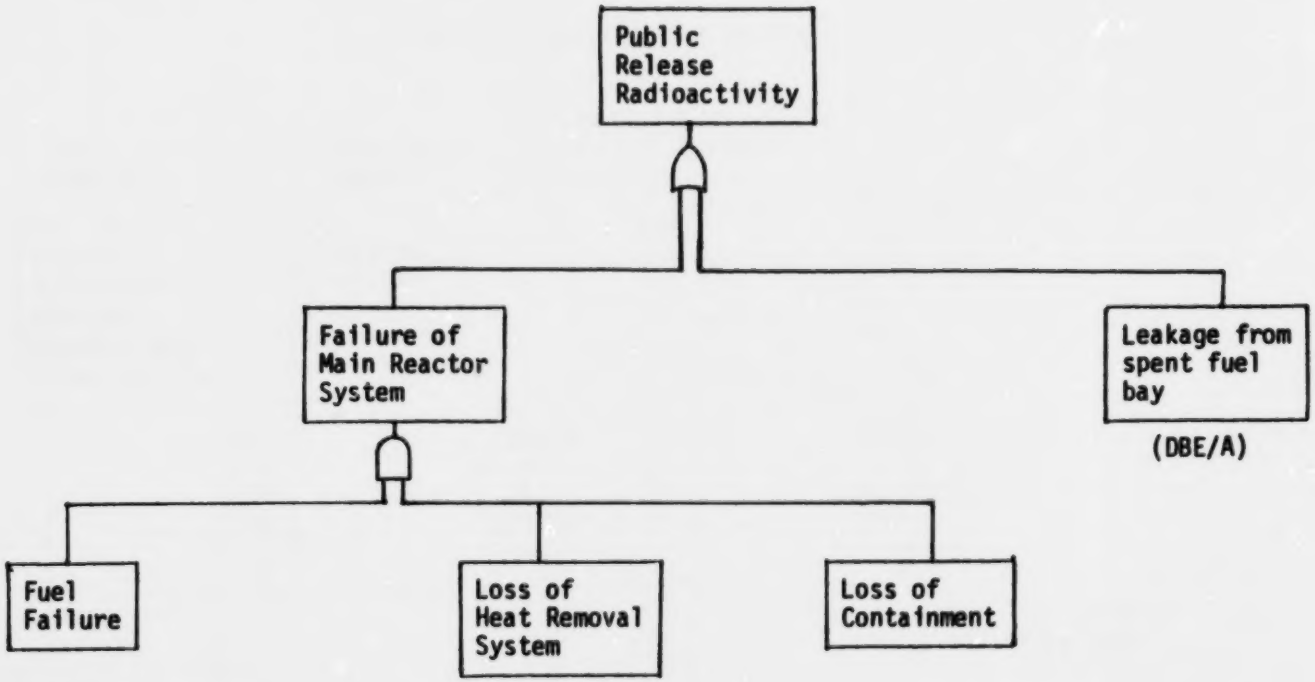


Figure 2.2 Main Branches of Fault Tree

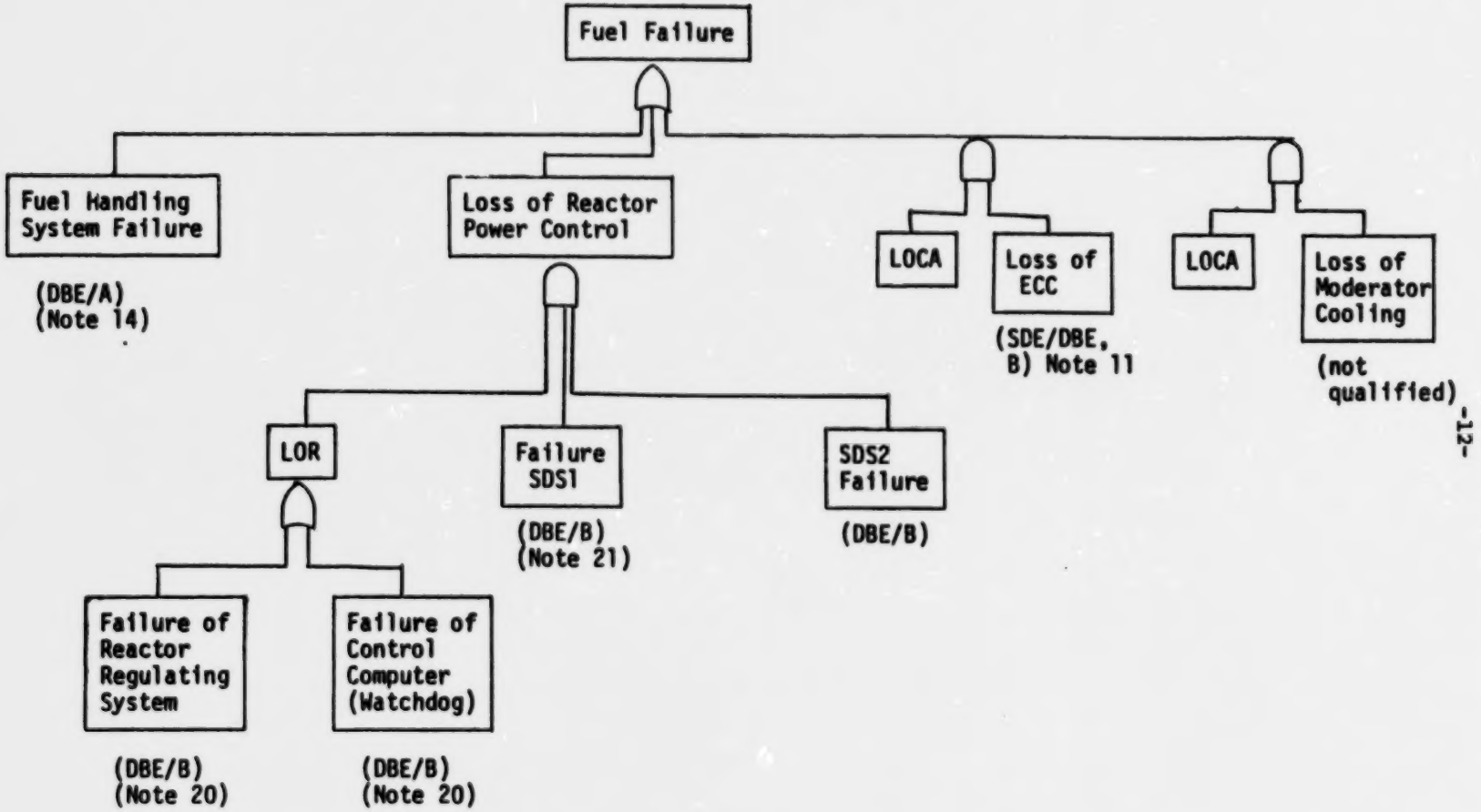


Figure 2.3 Fuel Failure Branch of Fault Tree

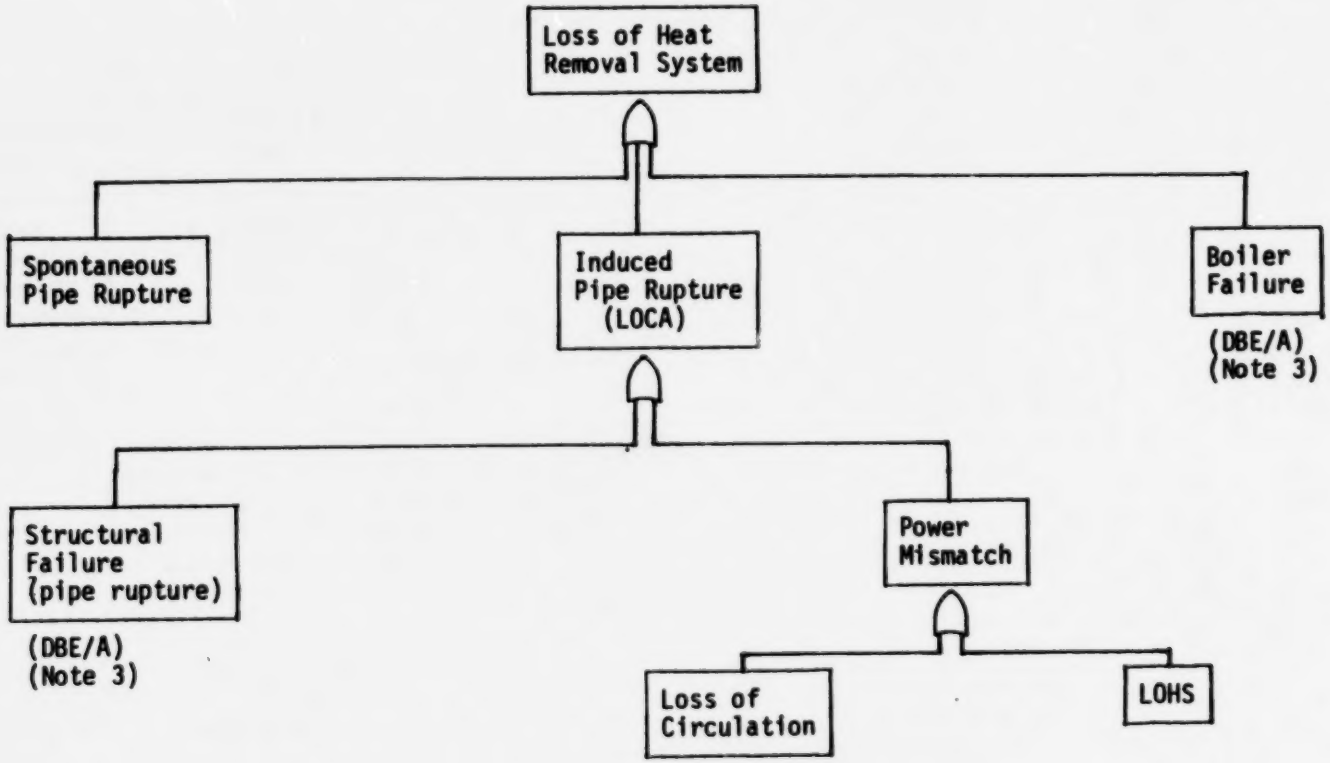


Figure 2.4 Loss of Heat Removal System Branch of Fault Tree

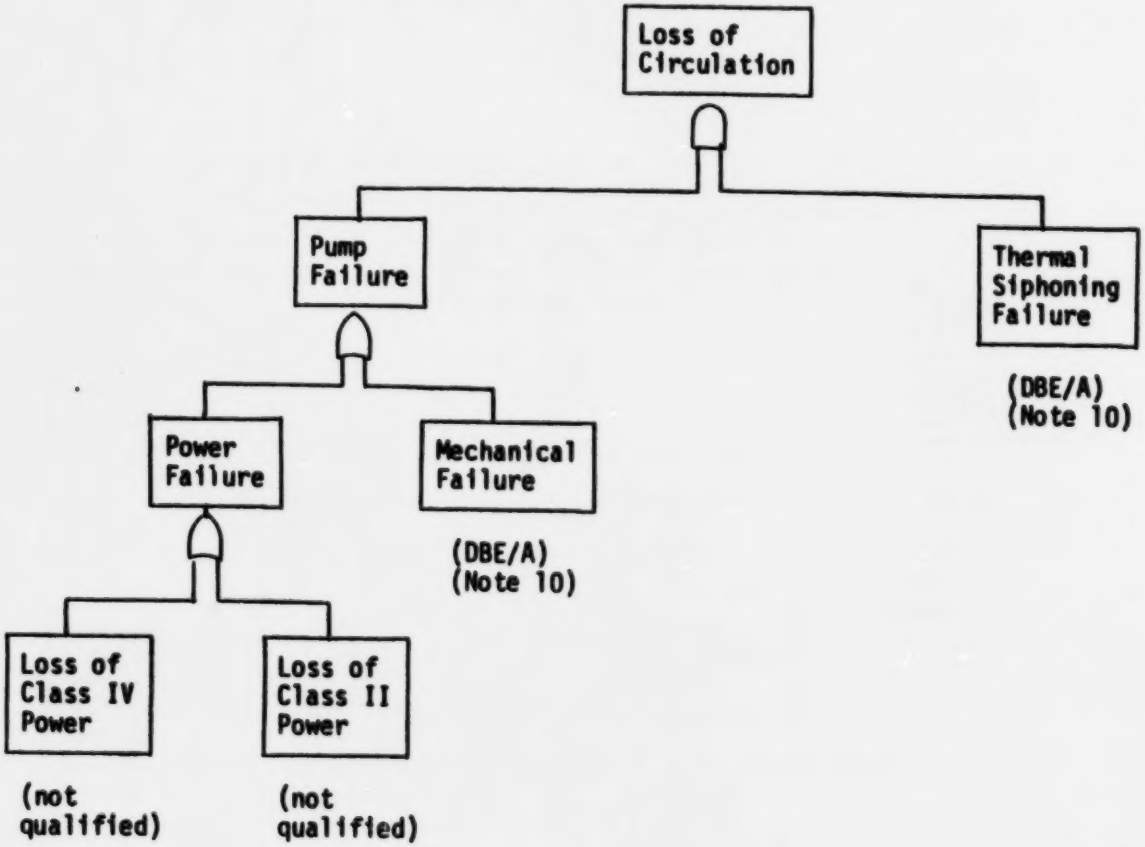
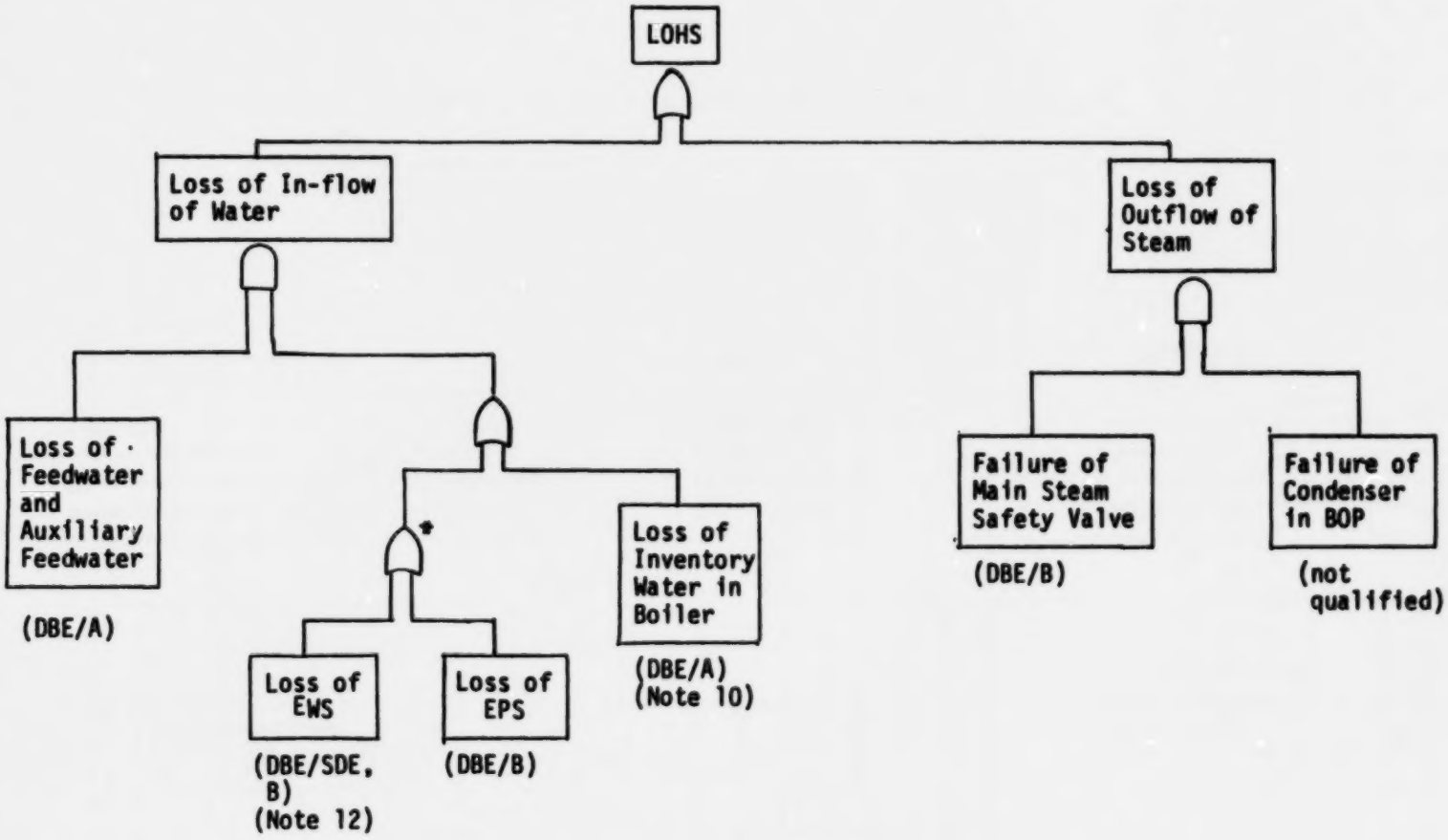


Figure 2.5 Loss of Circulation Branch of Fault Tree



*does not operate until 30 minutes of shutdown to remove decay heat

Figure 2.6 Loss of Heat Sink Branch of Fault Tree

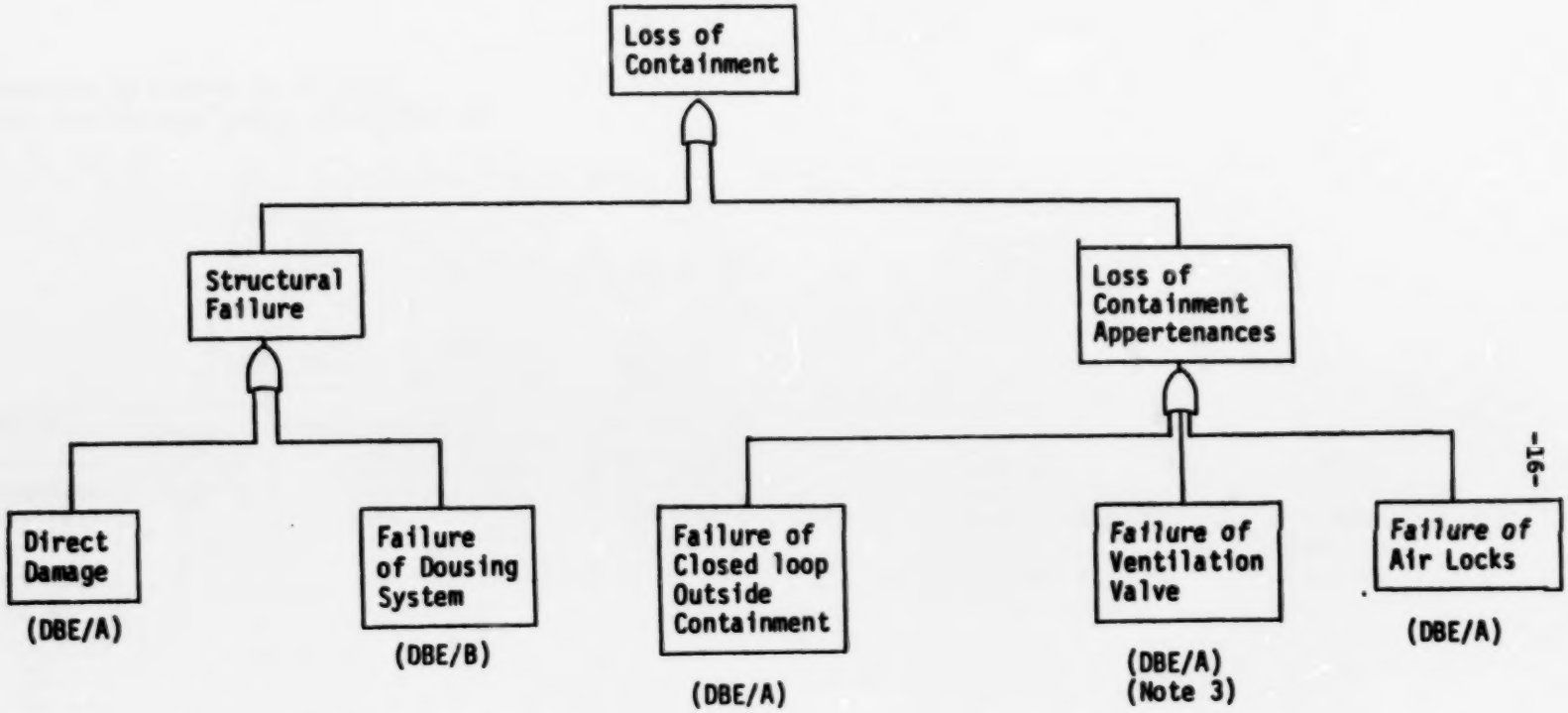


Figure 2.7 Loss of Containment Branch of Fault Tree

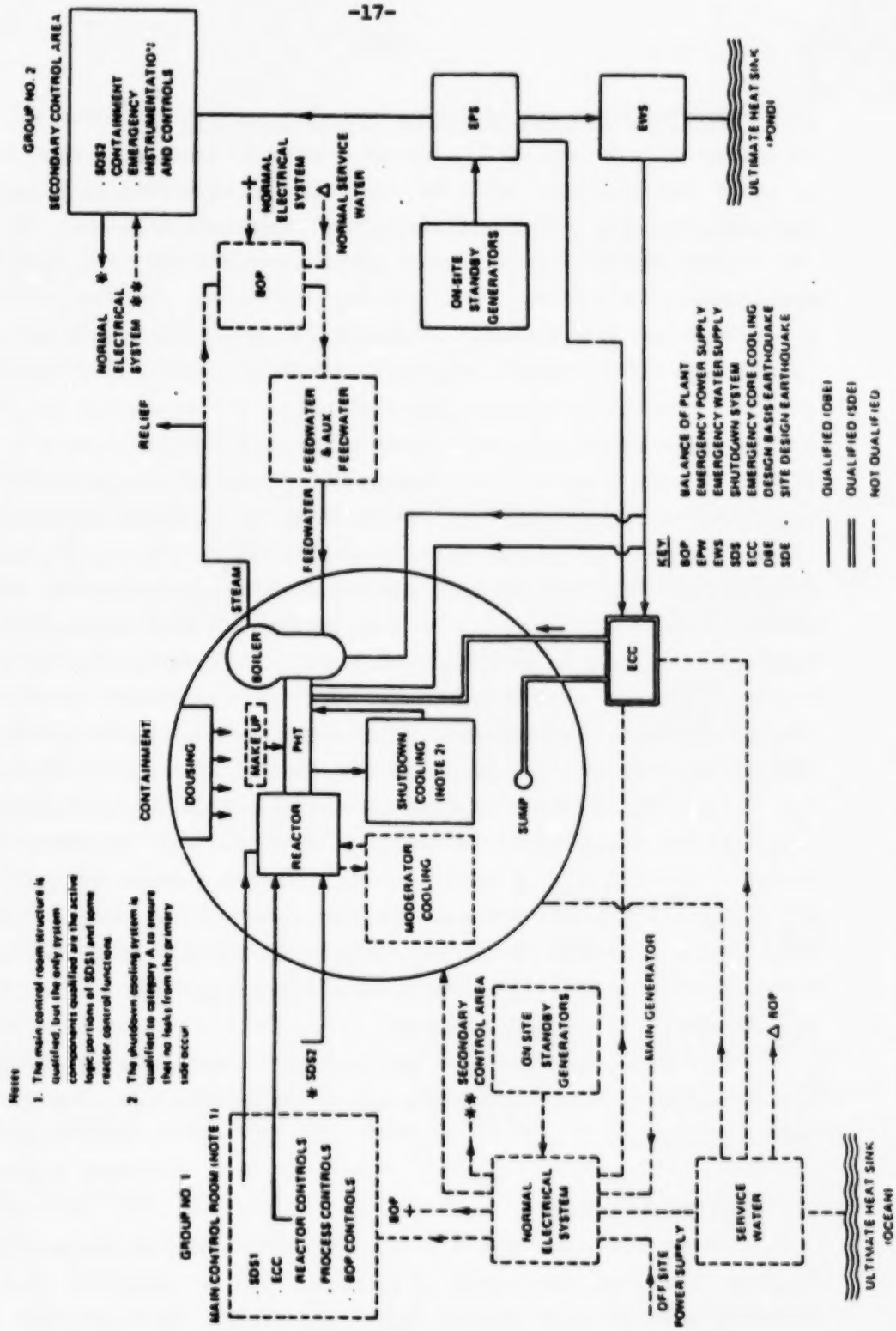


Figure 2.8 Seismic Classification and System Separation

3. METHODOLOGY FOR QUALIFICATION OF SAFETY SYSTEMS

Based on the fault tree study in Chapter 2, it is shown that during or after the occurence of a DBE, the likelihood of public release of radioactivity from a CANDU nuclear power plant will be remote, provided the various safety related systems which are qualified for a DBE remain operational.

Currently, the process to qualify a safety system consists of identifying the different components within the system and as far as possible, conducting seismic qualification of all identified components to the proper level and category of seismic protection. While it is a necessary condition that all components within the system need to be qualified, such component qualification is by no means sufficient to ensure that the system will operate as intended during and/or following an earthquake. In the seismic qualification of components, whether by analysis, by testing, or by a combination of both approaches, the component is deemed to have been qualified if, with proper input, proper output is obtained from the component when the component is subjected to simulated seismic disturbances. The component is essentially isolated from its inplant environment in the qualification procedure. Therefore, the interaction between qualified components and other components (qualified or unqualified) in the plant is neglected. In other words, there is the risk that a safety system fails to operate not because of the failure of its components due to earthquake shaking, but because the interaction between different components within the system is interrupted, or the qualified components are damaged due to the failure of neighbouring unqualified elements.

This chapter discusses the methodology to qualify a safety system for earthquake protection, in contrast to the seismic qualification of a safety component.

3.1 General Procedure

In order to ensure that a safety system is seismically qualified to a given level of earthquake protection, it is necessary that the following steps be observed:

(a) All components which are essential to the functioning of the safety operation within the system must be qualified, both for integrity and functionality.

(b) All qualified components must be housed within the plant in areas which are likewise qualified.

(c) All qualified components and the links between these components must be located such that their performance will not be impaired due to the failure or dislocation of adjacent unqualified systems.

The first requirement is basically a requirement of Component Qualification. This requirement is generally recognised by current practices. Suppliers of components related to the special safety systems are required to have their components seismically qualified with proper documentation. Guidelines for acceptable methods of qualification are available [8,9,11] and the nuclear industry as a whole has addressed this phase of system seismic qualification. The second requirement can be termed Location Qualification. It ensures that the components vital to the function of the overall system will not be damaged because of the failure of their supports. The third requirement ensures that the signals between different essential components are transmitted without interruption and will be called Interface Qualification in this report.

Currently, there are no set guidelines or procedures to carry out Location Qualification or Interface Qualification. Both these requirements relate the qualified components to the remaining part of the power plant. Therefore, procedures to implement these requirements depend to a large extent on the specific safety system and the specific power plant under consideration. For the present study, the SDS2 special safety system in the CANDU reactors at the Ontario Hydro Pickering B nuclear power generating station is taken as an example to illustrate the methodology referred to above concerning the qualification of a safety system.

3.2 Application of Methodology to SDS2 System

The SDS2 shutdown system is one of the two shutdown systems in the CANDU reactors at Pickering B station. The function of the system in

case of emergency is to inject gadolinium nitrate into the reactor core to poison the heavy water, with the purpose of shutting down the reactor. A schematic drawing of the SDS2 system is given in Fig. 3.1. The system consists of six poison tanks containing gadolinium nitrate. The poison can be injected into the calandria via six nozzles; each nozzle connects to one poison tank. The injection process is initiated by the opening of a series of quick opening valves which connect the poison tanks to a helium supply tank. The helium in the supply tank is under pressure and this pressure provides the driving force for the injection process once the quick opening valves are opened. The quick opening valves can be activated by signals that come from different initiators. Sensors are located at strategic points in the reactor system to monitor the state of the reactor at those points. If the states at one or more of these points deviate from their nominal values by more than a specified amount, one or more trip signals will be initiated and these signals will activate the quick opening valve and start the poison injection process.

There are seven initiating trip systems. Each of these systems can initiate the opening of the quick opening valves. To avoid unnecessary shutdown due to erroneous signals and also to provide redundant paths of transmission, signals for each trip parameter are transmitted by three independent channels (channels G, H and J). Arrangements are made at the opening valves such that the valves open when trip signals from two out of these three independent channels are received.

The operation of the SDS2 special safety system during or following the occurrence of an earthquake can be summarized in Fig. 3.2. The SDS2 system will operate if the following conditions are met:

(a) The earthquake causes a state of emergency in the power plant.
(b) This state of emergency is detected by one or more of the sensors which monitor different initiating trip parameters.
(c) Signals from the sensors are transmitted to the trip logic units.
(d) Trip signals from trip logic units are properly transmitted to the injection valves (quick opening valves).
(e) The injection valves function properly.
(f) There is adequate pressure in the helium tank.

(g) There is poison solution in the poison tanks.

(h) The connections between the poison tanks and the nozzles in the calandria remain intact.

(i) The nozzles in the calandria are not damaged.

The conditions stated above clearly demonstrate the necessity of having Location Qualification and Interface Qualification in addition to Component Qualification in order that the SDS2 system will function as a system.

3.2.1 Design Description of SDS2 System

The descriptions of the various parts of the SDS2 system can be found in a series of publications [12 to 15]. A brief description of the various parts of the SDS2 system is given here with the particular objective of describing the operation of the system under earthquake conditions. Components which are not essential for the operation of the SDS2 system under earthquake conditions (e.g., routine check and maintenance components) will not be considered here.

There are six zircaloy nozzles which penetrate into the calandria horizontally and at right angle to the calandria tubes. Each nozzle is connected to a poison tank. The poison tanks are cylindrical tanks mounted vertically on the outside wall of the reactor vault. The piping connecting the nozzle and the tank transverses through the vault wall. Each poison tank is connected to a helium header and the header is connected to the helium tank by six quick opening valves. The helium tank is normally pressurized to 1200 psi.

The six quick opening valves can be opened from signals from seven trip protection devices. Currently, seven trip protections are incorporated into the SDS2 system at Pickering B station and can be classified into two categories, namely, neutronic trips and process trips. There are two trips in the neutronic trip category: High Neutron Power Trip and High Rate Log Power Trip. There are five trips in the process category. They are (i) HTS Low Differential Pressure trip, (ii) HTS High Pressure trip, (iii) HTS High Temperature trip, (iv) Boiler Low Level trip, and (v) Reactor Building Differential High Temperature trip.

3.2.2 System Seismic Qualification for SDS2

Examination of the Design Descriptions of the various trip protections showed that all active trip components, including instrumentation tubing and equipment racks, are designed to the DBE level of seismic protection. Therefore, one of the basic requirements for system seismic qualification, namely, component qualification, has been carefully stated in the specification of the different trip protections.

In terms of location qualification, all the process transmitters, isolation valves and solenoid valves are located in Room 119. Electrical components such as temperature transmitters, alarm units, current relays, trip and test logic units, indicators for all channels, buffer relays and power supplies are located at the Unit Emergency Control Centre (UECC). Both room 119 and the UECC are designed to the DBE level. Readouts for trip parameters, trip buttons and trip testing facilities are located in the main control room (MCR) which is not qualified seismically. However, there are no active elements of the injection trip system in the main control room. Special arrangements are made such that the active automatic tripping element of the system will not be affected by common mode crosslinking fault of the poison injection system at MCR and UECC.

The equipment of each channel is located separately. If the equipment of two channels are not in separate rooms, then a separation of 18 inches is maintained, except at the control panel. To ensure that a minimum of 18 inches separation of the channel is maintained at all times, no active trip component is mounted on the control panel.

Since all active trip components are either located in Room 119 or at UECC, poison tanks are located outside the vault wall and the helium tank is housed in a seismically qualified area, the requirement of location qualification for the SDS2 system can be considered fulfiled.

The requirement of interface qualification has not been addressed in the Design Descriptions of the system. The implementation of this requirement can only be done when the routing of the cable trays connecting different active components is known. One needs to know the routing of cables from various sensors to either Room 119 and/or UECC. Also, one needs to know the routing from UECC to the injection valves,

and the arrangement of transmitters and trip and test logic within Room 119 and UECC. This information was not readily available at the time of this study since much of the final routing and component arrangements within the UECC had not been finalized. As such, it is not possible to indicate that the interfacing qualification requirements are completely met.

3.3 Summary

Component seismic qualification as currently done in practice is a necessary but not sufficient condition to ensure that the whole safety system is seismically qualified. Additional requirements such as location qualification and interface qualification are further steps needed to ensure the complete safety system will operate during or following an earthquake. While much attention has been given to component qualification of safety systems, there is not sufficient explicit emphasis placed on the interfacing of these components.

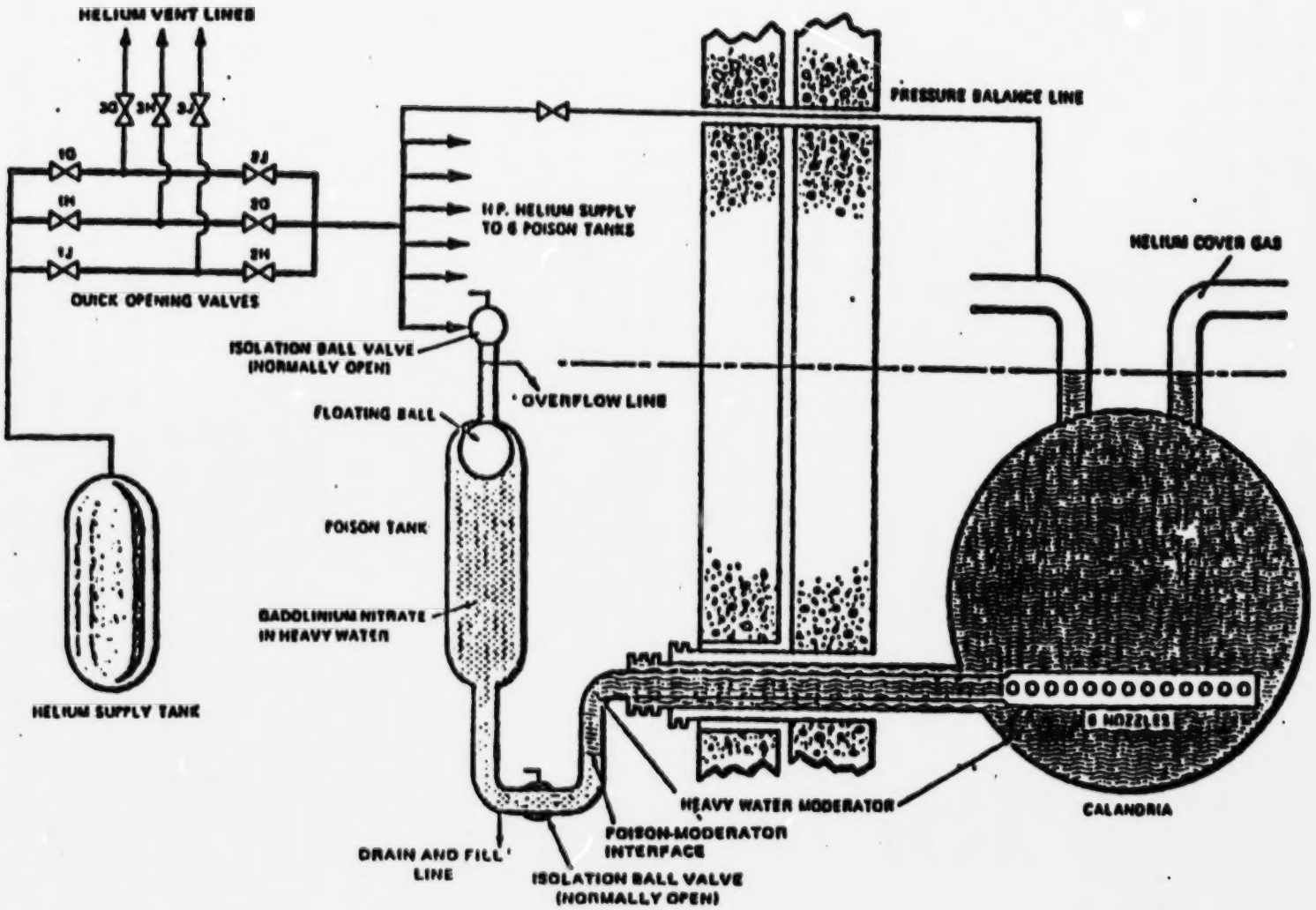


Fig. 3.1 Schematic of Second Shutdown System

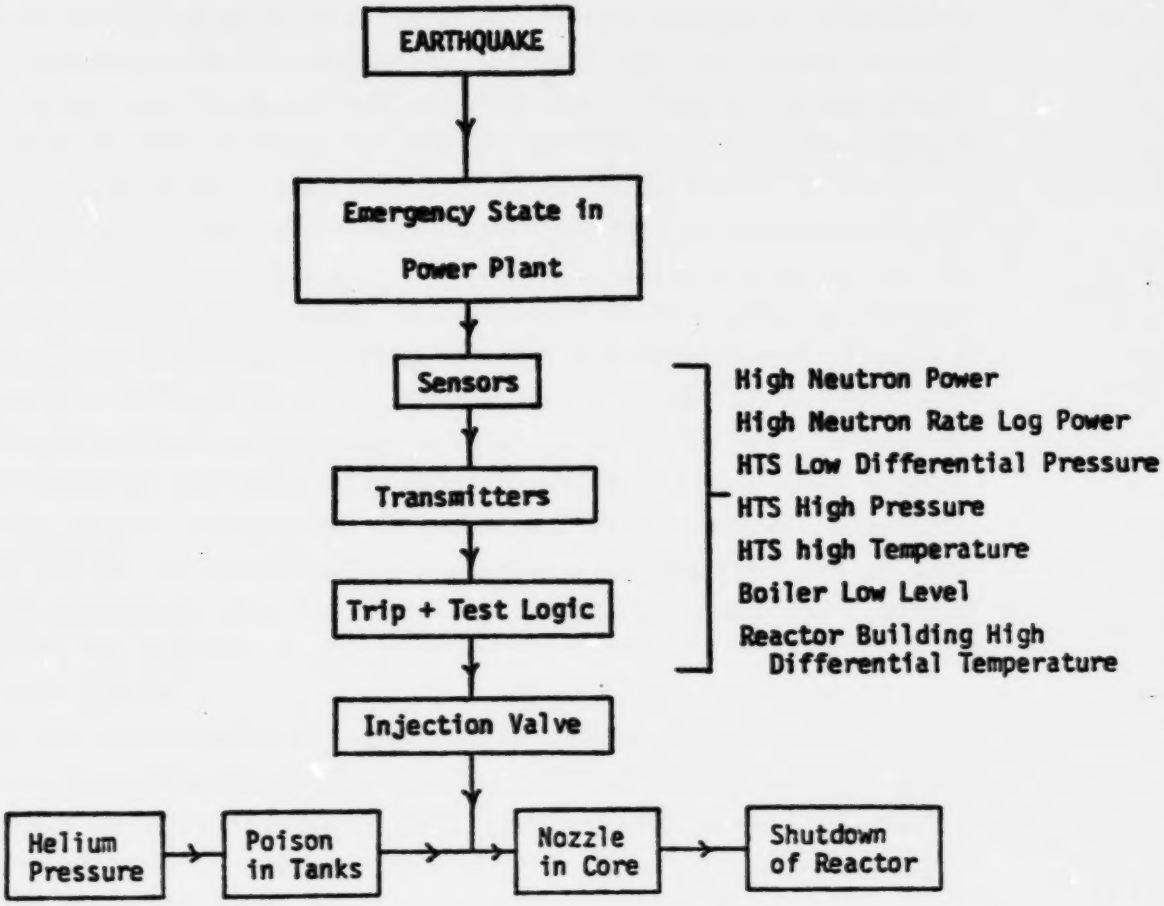


Fig.3.2 Operational Sequence of SDS2 System under Earthquake Conditions

4. COMPONENT SEISMIC QUALIFICATION

The susceptibility of equipment being damaged by an earthquake was clearly demonstrated by the earthquake at San Fernando Valley, California in February 1971. The need to provide guidelines on the seismic design and qualification procedures for equipment in power plants becomes evident. Special codes and standards have appeared in recent years to address the problem of seismic qualification of equipment in nuclear power plants. These current codes suggest a number of procedures for the seismic qualification of equipment; each procedure is considered as a viable alternative. In order to arrive at the most appropriate and practical qualification procedure, a knowledge of the availability and limitation of the different approaches for seismic qualification is needed. This section is the summary of a study to provide a broad overview on seismic qualification of equipment in nuclear power plants. The emphasis in this summary is to discuss the advantages, drawbacks, and limitations in each of the current methods used in the qualification of equipment and subsystems in nuclear power plants. More detailed information is contained in reference [5].

4.1 Seismic Qualification Steps

In a broad sense, seismic qualification of equipment involves three steps. The steps are: (a) identification of subsystems, (b) description of seismic environment and (c) obtaining response of the subsystem or equipment using acceptable qualification procedures.

4.1.1 Subsystem Identification

In seismic qualification of equipment, it is necessary to isolate the subsystems involved from the remainder of the plant. In the process, it is useful to recognize the interaction of the subsystems and the remainder of the plant. There are three considerations which determine such interactions.

First, it is necessary to evaluate the rigidity of the equipment involved. If the equipment is sufficiently rigid, there will be little dynamic amplification expected in a seismic environment. Based on studies of ground motion records, it is found that little dynamic amplification can be expected for systems with natural frequencies above

33 Hz. Therefore, it is current practice to consider a subsystem rigid if its fundamental frequency is above 33 Hz. Such equipment can be qualified based on static procedures, either analytical or experimental. The interaction between such subsystems and the supporting structure is restricted to the mass effect. In other words, the mass of the subsystem should be included in obtaining the overall structural response of the nuclear plant and the response of the subsystem can be taken as the same as its support motion. If the subsystem has natural frequencies below 33 Hz, some form of dynamic qualification procedure becomes necessary.

Second, it is necessary to judge whether the supported subsystem affects the overall response of the supporting structure and vice versa. The effect of coupling on the response of the subsystem and the primary system depends on their relative dynamic characteristics, mainly their relative mass and frequency ratios. In general, for any given frequency ratio, the coupling effect is larger for larger mass ratio. For any mass ratio, the coupling effect is more prominent when the frequency ratio is near or equal to unity. The coupling effect generally tends to amplify the response of the subsystem and deamplify the response of the primary system.

If it is determined that a particular piece of equipment has negligible interaction with the primary system, it will only be necessary to include the mass distribution of the equipment in the model of the primary system. The equipment can then be studied independently using responses (time-history or response spectrum) obtained at the floor elevation where it is located. If there is significant coupling between the equipment and the primary system, the equipment has to be studied in conjunction with the primary system. In such a case, no separate equipment support excitation needs to be generated because the subsystem will be excited directly through the primary system.

Third, equipment can further be classified whether it is "singly" supported or multiply supported. By singly supported, it is meant that the excitations on the equipment through its supports can be considered to be identical. Most equipment in a nuclear plant belong to this category. There are subsystems where the excitations at its supports cannot be considered to be identical. Piping is a prime example of a

multiple supported subsystem, since the system spans different elevations of the nuclear plant, and the excitations at different levels of the plant can be expected to be different.

In most cases of seismic qualification of subsystems, it is assumed (and often justifiably so) that the equipment considered is sufficiently light and small in size that it belongs to the class of uncoupled, singly supported subsystems.

4.1.2 Specification of Input

Each subsystem is qualified for a given expected seismic environment. The description of such environment for subsystem qualification is usually given in the form of floor response spectra. This is an indirect form of specifying the input motions at the support or supports of the subsystem. With a given ground response spectrum, there exists a variety of methods to obtain the floor response spectra at different locations within the plant. Most methods assume that the subsystems to which the floor response spectra will be applied can be uncoupled from the primary system.

The most straightforward method is to generate a series of ground spectrum compatible motions, apply them either one at a time, or in groups of three to simulate the three components of ground motions at the foundation of the structural model of plant. A dynamic analysis is then carried out to obtain the motions at points of interest. Based on these motions, floor response spectra are generated in the horizontal and vertical directions at various floors or other subsystem support locations of interest from the analysis of the primary system. The floor response spectra are then modified according to prescribed rules. Usually, this involves the broadening of the peaks in the floor response spectrum by $\pm$ 15% of the frequency at each respective spectrum peak [19]. This is a conservative measure to allow for possible pseudo-resonant response of the equipment due to the closeness of the equipment natural frequency to the primary system frequencies as a result of the variability of material property parameters used in the modelling of the equipment.

4.2 Procedures for Equipment Qualification

This step is usually considered the main thrust in any seismic qualification studies. In general, there are three approaches to seismic qualification of equipment and subsystems. They are: (1) by analysis (ii) by testing and (iii) by a combination of analysis and testing.

Before getting into the details for each approach, it must be recognised that there is one major difference between the approaches of qualification by analysis and by testing. Each approach uses different parameters to monitor the response of the system. In the case of analysis, the maximum stress, strain, load or deformation (structural mechanics quantities) are the key parameters for acceptability. In testing, the operability or failure to operate (functionality) is the focal point for acceptability. While the stress, load or deformation of the analytical approach provide a link to component fragility through other structural mechanics disciplines such as fracture mechanics or buckling analysis, it is often difficult to extrapolate operability data from testing to estimate the fragility state of the component. The two approaches of seismic qualification are not readily interchangeable because each measures a different response quantity. Therefore, the use of one or the other depends on both judgment of which method is most appropriate, as well as the question of economics for each method.

4.3 Qualification by Analysis

In the analytical approach to seismic qualification, the actual component or subsystem is modelled by a mathematical model. Subjected to seismic excitation, a set of structural mechanic parameters such as stress, load and deformation is used to quantify the response of the subsystem. Judgment on qualifying the subsystem is based on comparison of the calculated responses to allowable responses. Broadly speaking, the modelling can be classified into static modelling and dynamic modelling. Static modelling is used when the subsystem is sufficiently rigid so that its fundamental frequency exceeds 33 Hz. For more flexible subsystems, dynamic modelling is necessary to take into account the possible dynamic amplification effect due to seismic excitations.

4.3.1 Static Coefficient Method

The static coefficient method is commonly used for seismic qualification of simple systems of high rigidity such as small wall mounted control panels, floor mounted motors and pumps. The procedure used is to apply the product of a specified loading coefficient and the peak spectral acceleration at the center of gravity of the equipment and a stress analysis is carried out to compute the internal stresses of the subsystem and also the loads on bolts or legs at the support due to overturning effect. The static coefficient method has the advantage of being simple to apply and it is conservative for systems of high rigidity.

4.3.2 Dynamic Methods

For subsystems with resonance below 33 Hz, dynamic modelling of the system to account for its mass, damping and stiffness properties becomes necessary. There are two common types of dynamic modelling in seismic qualification analysis: stick model with lumped masses and finite element model. Stick models with lumped masses are most commonly used models for the analysis of subsystems. They are appropriate for relatively stiff systems if the objective of the analysis is only to obtain overall response of the system such as displacements, accelerations and overall forces. Equipment commonly modelled by stick models include pumps, compressors, valves, cooling fans, motors, generators, transformers, cable trays, fuel rod clusters, control rod and drives, and pipes.

Finite element models should be used for the modelling of systems if detailed stresses distributions are required in local areas. Also, this type of modelling is appropriate if the system behaves predominantly in the shell or plate type of modes. Depending on the degree of symmetry possessed by the system, axisymmetric finite element may be used to reduce the complexity and eventual cost of the analysis. Typical components modelled by finite element models are large vessels, large pipes and reactor internals.

The methods of solution to obtain the response of the mathematical model of the equipment depend on the form of input used. Broadly speaking, it is most convenient to use time domain solution techniques

when time histories are used as input and frequency domain solutions when floor response spectra are used as input.

Using time histories as input, there are in general two commonly used procedures to obtain the response of the subsystem, namely, direct integration and modal superposition. The direct integration approach obtains the solution to the equations of motion simultaneously for each time step of the input motion by numerical techniques. The modal superposition method consists of the use of normal coordinates to transform the coupled equations of motion to a set of independent normal coordinate equations. The dynamic response is thus obtained by solving separately for the response of each normal coordinate and then superposing these responses to obtain the response in the original coordinates. The modal superposition method is a very convenient approach for response analysis, and is useful to provide an insight on the dynamic characteristics of the system. The main drawback of this method is that it applies to linear dynamical systems only.

If the input is given in terms of floor response spectrum, one can obtain the maximum response of the subsystem by the response spectrum technique. This technique is strictly applicable to linear models only. In this technique, the dynamical equations of motion are uncoupled by means of modal transformation. The maximum response for each mode is obtained. The analyses of subsystems are then performed using a modal superposition procedure, where individual modal maxima is combined using the square root of sum of squares (SRSS) procedure. To allow for the effect of closely spaced modes, a variety of procedures have been proposed such as taking the absolute sum of the response of the closely spaced modal responses and then combining this sum with the other modal responses using the SRSS procedure.

A further approximation is necessary to combine the responses of the subsystem due to excitations (in terms of spectra) in each of the three global directions at the support. The current practice is to combine the responses by using the SRSS of the codirectional responses caused by each of the three spectra at a particular point in the subsystem. The SRSS combinational rule for codirectional responses is based on the assumption that the excitations in the three directions are essentially uncorrelated. Studies have been made to indicate that

subsystem responses obtained using the SRSS rule for codirectional responses are on the conservative side.

The time history method is considered to be more precise than other methods available. It retains the phase and frequency content of the motions involved. It can be used to include nonlinear effects. The main uncertainties associated with this method are: (a) development of artificial time histories to envelope the given floor response spectrum for qualification; (b) the possibility of filtering out of high frequency components of motion due to the time step used in the analysis; and (c) the derivation of the damping matrix used in the analysis primarily from modal damping values. Usually Rayleigh's damping, i.e. proportional to mass and stiffness, is used which can accommodate damping data from two modes. Depending on the selection of modes for the computation of Rayleigh damping and the type of problem involved, the response can be significantly affected.

In comparison with the time-history method, the response spectrum method requires less computational effort to obtain the maximum response of the subsystem. Therefore, it is useful at the preliminary design stage, and also in cases where a detailed time-history analysis is judged to be unnecessary. However, this method does not take into account the phase relationships of the modal response. Also, rigorous nonlinear analyses cannot be performed using this method. Because the phase relationship between modes, and between motions in three perpendicular global directions are missing, there exist inherent uncertainties in the modal and directional combination of responses.

4.4 Qualification by Testing

Qualification by testing is the most positive method in demonstrating the seismic resistance of subsystems. It is commonly used to qualify electrical equipment which is difficult to analyse and whose functionality before, during, and after an earthquake has to be assured. Again, depending on the natural frequencies of the subsystem, it may be qualified by a static test (for subsystems with no natural frequencies below 33 Hz), or by dynamic test (for subsystems with natural frequencies below 33 Hz). The most common form of seismic qualification by dynamic testing uses shake tables. The component to be qualified is

mounted on a programmable shake table and the table provides the required base motions to the component. There are a variety of acceptable methods allowed by the test standards [9,11].

During an earthquake, the shaking of a subsystem is in general three dimensional and can be described by motions in the vertical direction plus motions in two perpendicular horizontal directions. The best simulation to such situation will be to provide test motions simultaneously in three directions (multi-axial testing). While multi-axial testing provides a good simulation of the actual environment, phasing of the motions to be used in the different direction remains a major uncertainty. Currently, multi-axial testing is being carried out either with the phase of the different motions specified at arbitrary values, or using random phasing. There is not sufficient study to ensure the current procedures are either representative of the seismic environment or that they will lead to conservative results.

However, there are very few shake tables that can provide simultaneous motions in three directions. Most multi-axial shake tables provide motions in two directions only (usually vertical and horizontal). Another alternative to simulate excitations in the vertical and horizontal directions is the use of inclined shake tables. These tables are essentially uniaxial tables with movements at specified directions inclined to the horizontal direction. Therefore, they provide in-phase, or 180° out-of-phase vertical and horizontal excitations to the specimen. The most common form of shake tables are uniaxial shake tables, providing motion in one direction only, either horizontally or vertically.

Most equipment has minimal coupling of responses in the three perpendicular directions. Under such circumstances, one can expose the equipment to the overall seismic environment using a series of uniaxial tests. By proper orientation of the specimen, the equipment is subjected to dynamic disturbances along its three reference axes, one axis at a time. To allow for possible strong directional response coupling, a 40% increase in excitation level is recommended for uniaxial testing. With this suggestion, the uniaxial testing often leads to a more demanding test than the corresponding multiaxial test. The main disadvantage of using uniaxial testing in such case is the extra testing

time and effort required to set up the specimen with the appropriate axis parallel to the direction of shaking.

To generate the time history for the shaking test, there are a number of alternatives to synthesize a waveform to envelop the specified response spectrum. They can be broadly classified into three categories: (i) single frequency motions, (ii) multi-frequency time history motions and (iii) broad band random motions. Depending on the location of the test subsystem, the actual seismic motions can be relatively broad band in frequency content (location close to ground level), or narrow band in which one frequency may dominate (floor supported items).

In the single frequency category are motions such as sine beats, decaying sines, short duration sinusoids and sweep tests. A detailed study on the relation of these motions and its effects on the test specimen is given by Wilson [2].

When the support motion for the subsystem is broad band, a random wave form can be obtained by a random motion generator. By means of band pass filters, the motions can be adjusted to approximate the desired specified response spectra. The sine beat motion is sometimes used to superimpose on a broad band random motion to create a narrow band motion suitable for testing floor mounted equipment.

4.5 Comparison of Qualification Approaches: Analysis or Testing

As stated at the beginning of this chapter, analysis and testing represent two distinct approaches to seismic qualification of equipment and subsystems. The choice of one over the other depends on a number of factors. Among these factors are the purpose of the qualification (for functionality or structural integrity), sizes and weights of the equipment, feasibility of simulating actual operating conditions, and costs.

In general, the same input motion in the form of an in-structure response spectrum would be specified for either method. The advantages of testing are:

(a) Modelling assumptions such as damping, nonlinearities, and boundary conditions are not required, since significant dynamic characteristics, nonlinear effects, etc. inherent in the subsystem will show up during the test.

(b) Defects on small items which may not even be included in the mathematical model can be detected.

The disadvantages of testing are:

(a) Generation of a time series is required in the process. Currently, there is no procedure which is capable of exactly matching the actual test response spectrum (TRS) with the specified response spectrum (SRS). Often, a large amount of conservatism is introduced, particularly at the high frequency end of the spectrum.

(b) For many equipment, it is not easy to simulate the operating condition during testing. Typical example of such equipment are those where thermal and/or fluid flow are important.

(c) Unless fragility testing is included, the safety margin is not known and predictions of responses to withstand higher level of excitation cannot be made.

(d) There are size and weight limitations to carry out testing of subsystems on shake tables. Currently, the largest table in North America with good response control up to 33 Hz is limited to about 3m by 3m in plan dimension with a weight limitation of 5 tons.

(e) Usually, the cost involved is higher than qualification by analysis.

Many of the disadvantages listed above for testing appear as advantages for qualification by analysis. Among the advantages of qualification by analysis are:

(a) Complex operating conditions such as thermal and fluid flow effects can be incorporated in the model.

(b) Design changes can be made to reinforce weak areas in the equipment. The margin of safety can be estimated for different postulated failure modes.

(c) Weight and size limitations do not exist. Also, the input to the system is not limited to test set up availability. Simultaneous three axes excitation can be incorporated in the analysis.

(d) None of the "life" of the component is used up. This can be an important advantage if fatigue is one of the primary modes of failure of the system.

The main drawback in qualification by analysis is the possibility of human error through modelling. Modelling accuracy depends on the

analysts' skill in representing the subsystem and its boundary conditions in an analytical model. The analytical model has to be sufficiently detailed to include all probable modes of failure under seismic excitations. The improper representation of boundary conditions and treatment of nonlinear gap effects can have a large effect on the calculated response, although such modelling uncertainties are not readily quantifiable in general terms.

Assuming the mathematical model is properly formulated, there is the uncertainty of material properties and representation of the energy dissipation mechanisms which are commonly lumped under the heading of equivalent viscous damping. Accurate representation of damping is very difficult because the lack of knowledge of the energy dissipation mechanisms involved. The equivalent viscous damping value is a function of the materials used, the construction details and the stress level. Guidelines on damping values for different components are available and are in general on the conservative side compared to experimental data.

One important disadvantage in qualification by analysis is that it is difficult to demonstrate functionality. Normally, functionality is inferred through evaluation of structural mechanics parameters such as stresses or deformations below threshold values.

4.6 Qualification by Combined Analysis and Testing

A comparison between qualification by analysis and by testing shows that each method has its own advantages and shortcomings. The combined analysis and test method is a hybrid approach to seismic qualification of subsystems which makes use of the advantages of both methods. Two commonly used procedures are given below:-

(a) A vibration test is performed and the dynamic characteristics and system parameters are identified, using identification techniques. A simplified analytical model is then generated and the model parameters are adjusted to match the test identified values. This test calibrated model is then used to generate response spectra for instruments and appendages on the system. The appendages are then qualified either by test or by analysis.

An example of such procedure is the requalification of equipment at existing nuclear facilities. Based on the field test data on the

supporting structures such as auxiliary building, piping network, control panel etc., response spectra can be generated for the qualification of instruments and appendages.

(b) Another application of combined analysis and testing is the verification of analytical models and model assumptions. Generic type qualification of systems are best performed by this technique. Vibration tests are performed on selected sets of systems, and analytic models are generated. These analytic models are adjusted to match the test data and then extended to cover other similar systems. Thus, the test supported model is extended to other systems and qualification can then be performed by analysis. These analytical models can also be used to qualify the system for other facilities. Examples of this type of qualification are cabinets (multi-bay type), electric motors, and cable trays.

4.7 Summary

Seismic qualification of equipment in a nuclear power plant is a complex task. First, there is a large variety of equipment and subsystems that need seismic qualification. They vary greatly in terms of size, shape, weight and complexity. Depending on their functions within the plant, different criteria are necessary to qualify them. Also, the seismic environment faced by the equipment can vary greatly, depending on their location within the plant, their stiffnesses and their masses relative to the plant. To encompass all possible circumstances, current standards allow a variety of approaches as suitable procedures to be used. In this review, a broad outlook of the current procedures is presented. The emphasis here is on critical comparisons of the different approaches, and within each approach, the different methods of seismic qualification.

5. INVESTIGATION OF TESTING PROCEDURES

As indicated in the previous chapter, there is considerable concern about the way in which testing procedures simulate anticipated seismic floor motions. While there is no evidence that current procedures have led to the installation of equipment which is underqualified, there is a real need to ensure that test procedures provide a reasonably realistic simulation of seismic floor motions which equipment is expected to withstand should an actual earthquake occur.

In order to simulate actual seismic floor motions, it is necessary to be able to properly characterize the properties of such motion; a portion of this investigation deals with the appropriate characterization parameters. The application of these parameters to determine the suitability of various single frequency testing procedures are also included. Real floor motions are multi-frequency in nature, and it is therefore necessary to consider the evaluation of multi-frequency time-history testing. This report includes a description of the testing of an instrument cabinet which was done as part of this evaluation.

5.1 Characterization of Seismic Floor Motions

This section will present a brief description of several parameters which have been proposed to be suitable for use in the characterization and classification of earthquake induced motions and structure or equipment responses. A detailed description of these parameters can be found in a report of the 1979-80 phase of this research programme [2]. The six parameters are maximum acceleration, response spectrum, cumulative damage, cumulative RMS function, duration of strong motion and root-mean-square acceleration. The first two might be considered "classical" parameters while the other four are more recent in origin; the sources of these "new" parameters are indicated in the descriptive paragraphs which follow.

The simplest parameter to obtain from a time history is the maximum acceleration. Its use as a description, however, implies that all time histories are similar in duration and frequency content and this is seldom the case. Its wide use is probably bound up in historical roots and the fact that it is used to bound the high frequency end of the

response spectrum. Unfortunately, time histories having the same maximum acceleration can lead to completely different structural responses.

The second parameter is the response spectrum. A response spectrum is a plot of the maximum response versus natural frequency for different single degree of freedom systems, having the same level of damping, subjected to a particular time history. Response spectra are usually defined for the ground and for each floor of the structure. These response spectra are normally defined over the range of frequencies from 1 to 33 Hz.

The third parameter is referred to as the "cumulative damage process", which provides a technique for measuring equivalency between time histories, in terms of the equivalent number of cycles of a uniform amplitude motion required to accumulate the same damage as the random fluctuations in the time history. This process was first applied to seismic problems in nuclear power plants by Duff and Heidebrecht [16]. The equivalent number of cycles is obtained by using the simple yet accurate cumulative damage theory proposed by Miner [17].

The particular definition of equivalent cycles used in this study is given by

$$N_{eq} = \frac{1}{2} \sum_{i=1}^{n} \left(\frac{R_i}{R_p}\right)^{\beta}$$

in which n is the total number of cycles

R_p is the maximum amplitude

R_i is the amplitude of cycle "i" and

β is a parameter related to material properties and test conditions.

The other three "new" parameters were applied to studies of strong ground motion characteristics by McCann and Shah [18]. The cumulative RMS function provides a time-wise indication of how the strength of a particular motion builds up and then decays. The function is defined as

$$CRF(t) = \left\{\frac{1}{t} \int_{o}^{t} a^2(\tau)\, d\tau\right\}^{1/2}$$

in which $a(\tau)$ defines the acceleration time history.

The duration of strong motion can be defined qualitatively as the time taken to build up from the onset of motion to the beginning of the decay in the cumulative RMS function. Detailed expressions for duration of strong motion have been determined [2] but are not shown here.

The final parameter, root-mean-square acceleration (A_{rms}), can now be defined in terms of the cumulative RMS function and the duration of strong motion. Simply stated, the RMS acceleration is defined as the final value of the cumulative RMS function when it is evaluated from the beginning to the end of the time interval containing the strong motion. Figure 5.1 illustrates CRF, duration and A_{RMS} for a typical earthquake ground motion record.

The use of some or all of these parameters would allow for the multiple parameter description, as opposed to the single parameter description, of seismic motion. This should provide for a more accurate description of seismic motion.

5.2 Evaluation of Single Frequency Testing Procedures

Single frequency motions of various kinds are commonly used in seismic qualification testing. The motions evaluated in this report are constant amplitude limited duration sine waves, sine beats and decaying sinusoids, as shown in Fig. 5.2. In actual testing, each single frequency motion is repeated at relatively closely spaced frequency intervals (e.g. one-third octave) over the frequency range of interest, typically 1 to 33 Hz.

The characteristics of these three types of single frequency motion, using the parameters discussed in the previous section, were studied in considerable detail [2]. By selecting appropriate durations and amplitudes of motion, a certain amount of equivalence can be obtained, as can be seen in Table 5.1. This table shows situations in which each of the three motions has the same RMS acceleration, peak response spectrum ordinate and cumulative damage cycles N_{EQ}. However, the three motions do not equally simulate actual seismic floor motions as can be seen by examining the cumulative RMS function in Fig. 5.3. This figure shows that the energy build-up, as given by the CRF, is very rapid for the sine and decaying sine motion, but is much more gradual for the sine beat. By comparing this build-up with that shown for

actual seismic ground motion in Fig. 5.1, it can be seen that the sine beat motion provides the best simulation of the characteristics of actual seismic floor motions. Consequently, it is recommended that sine beat motion can be used whenever single frequency methods are appropriate.

5.3 Multi-Frequency Time-History Testing

Actual seismic floor motions are multi-frequency in nature and multi-frequency time-histories are often used in seismic qualification testing. In most cases the primary requirement is that the test motion have a response spectrum which envelopes the response spectra of floor motions which are anticipated due to actual earthquakes. This section describes an experimental programme which was used to assess the implications of such an approach. The actual testing and results are described in the next section. The full programme of testing is described in a separate report [4].

Fig. 5.4 provides a schematic diagram of the methodology used in this phase of the investigation. An ensemble of twelve different actual seismic ground motion time-histories were selected (from among the large number currently available) by considering such factors as local site conditions, magnitude, maximum acceleration, duration and source distance.

These twelve ground motions were then applied as inputs to a mathematical model (provided by Atomic Energy of Canada Limited), which is a lumped masss representation of a 600 MeW CANDU nuclear power plant. The model, which consists of four major groups of structural components (foundation base slab, containment structure, internal structure and reactor vault) is shown in Fig. 5.5. To indicate the relationship between this model and the real nuclear power plant structure, Fig. 5.6 shows a cut-away view of a typical CANDU unit with model mass numbers superimposed.

The frequency analysis yielded an ensemble of floor motion time-histories at typical locations at which qualified equipment is located; masses 4 and 12 were used in this study. These time-histories were then normalized so that the maximum acceleration of each floor motion was 0.25 g. Individual floor response spectra were then computed

for each normalized time-history.

The analytical phase was completed by superimposing all the twelve individual floor response spectra at each of the two locations to create an envelope response spectrum for each location. Each envelope response spectrum was then broadened, using the methodology approved by the U.S. Nuclear Regulatory Commission [19], in order to create a design response spectrum for the particular location. Typical envelope and design response spectra are shown in Fig. 5.7.

The test specimen used in the experimental phase was an instrument cabinet typical of those used in nuclear power plants. The cabinet was provided through the co-operation of AECL and Ontario Hydro. In order to bring the cabinet natural frequencies down into the range of the predominant floor motion energy, a dead weight of approximately 700 pounds was attached to the top of the cabinet. The cabinet with attached weight is illustrated in Fig. 5.8.

The actual experimental phase consisted of two groups of tests. In the first group, the individual floor motion time histories were used as table motions. The cabinet responses to these motions represent an ensemble of responses which would be expected during actual siesmic events. This ensemble was then used as a "base" by which to evaluate the appropriateness of a multi-frequency testing methodology using the design response spectra obtained by broadening the envelope of the individual response spectra, as described previously.

In order to conduct the second group of tests, composite floor motion time histories were created. These composite motions were composed of superimposed sine beats of different frequencies and were developed so that their response spectra enveloped the corresponding design response spectra. These composite time histories were then used as table motions in the second group of tests.

5.4 Instrument Cabinet Test Results

The response of the cabinet was monitored by three accelerometers, two recording response in the direction of excitation at the top and mid-height and one recording transverse response at the top of the cabinet. Typical response time-histories are shown in Fig. 5.9. All responses were recorded and stored for analysis which included the

determination of the following parameters: the duration of strong motion, the RMS acceleration, the equivalent number of damage cycles, amplification of peak acceleration (cabinet response to table), and the ratio of RMS acceleration to peak acceleration.

Four of the above parameters were analysed statistically in order to compare the responses due to "actual" and composite time histories. The mean, standard deviation, maximum and minimum values for each parameter were obtained for all responses at each cabinet accelerometer location and for each of the two building locations (masses 4 and 12 in Fig. 5.6). These statistics were based on between 32 to 34 sample values for the "actual" time histories and 3 sample values for the composite time histories. The results are detailed in reference [4] and summarized in the following paragraphs for the four parameters which were analysed, namely peak acceleration amplification, RMS acceleration amplification, number of equivalent damage cycles and duration of string motion. Typical results are given in Table 5.2.

The results for the "actual" floor motions show considerable variability, due to the differing earthquake characteristics, as well as nonlinearities in cabinet response. Nonlinear cabinet response was observed because each time history was applied using different levels of excitation and the response amplification, damage cycles and durations varied with excitation level.

The results show that both the peak and RMS acceleration amplifications are substantially larger for the ensemble of "actual" time histories than for the composite time histories. This is true whether one looks at the mean or maximum values of amplification. While the reasons for this result cannot be determined directly from the experimental data, it does indicate that a simple enveloping of response spectra is insufficient to ensure that all response parameters will also be enveloped.

On the other hand, the composite time histories produce larger number of equivalent damage cycles and longer strong motion durations than are produced by the "actual" floor motions. This is likely due to the fact that the nature of the sine beat superposition used in creating the composite time history is such as to ensure that the strong motion duration is very near the full 30 second duration of the time history.

The longer duration of the composite time histories also contribute to a larger value of the number of equivalent damage cycles.

The general conclusion of this study is that the simple enveloping of a design response spectrum will not necessarily yield the best composite time history for testing a piece of equipment. If the amplification of motion within the piece of equipment is important, then it may be necessary to modify the composite time history (e.g. by increasing its amplitude to produce a larger response) or to use another composite time-history which produces larger amplifications. It may also be appropriate to use a small "sub-ensemble" of actual time-histories which are known to have the capability of producing large amplifications.

TABLE 5.1 EQUIVALENCE OF SINGLE FREQUENCY MOTIONS

CHARACTERISTIC	LIMITED DURATION SINE	SINE BEAT EQUIVALENT	DECAYING SINE EQUIVALENT
No. of cycles	5	7	11
Maximum acceleration	1.0 g	1.18 g	1.32 g
Strong phase RMS aceleration	.707 g	.707 g	.707 g
Peak Response Spectrum Ordinate (1 % damping)	13.5 g	13.5 g	13.5 g
Duration of Strong Motion (cycles)	5	5	3.3
N_{eq} (norm. to 1 g)	5	5	5

TABLE 5.2 TYPICAL INSTRUMENT CABINET TEST RESULTS

(Mass 4 motions, top cabinet accelerometer in direction of table motion)

	Response Parameter	Minimum	Maximum	Mean	Standard Deviation
1.	Amplification of Peak Accelerations --				
	Actual	1.44	9.82	3.87	2.06
	Composite	2.71	4.27	3.41	0.79
2.	Amplification of RMS Accelerations --				
	Actual	1.62	16.68	6.30	3.85
	Composite	4.18	4.39	4.29	0.11
3.	Equivalent Damage Cycles --				
	Actual	6.31	33.46	14.59	6.48
	Composite	42.14	55.52	46.81	7.55
4.	Duration of Strong Motion (seconds) --				
	Actual	4.48	26.90	11.49	7.36
	Composite	28.38	30.14	29.40	0.91

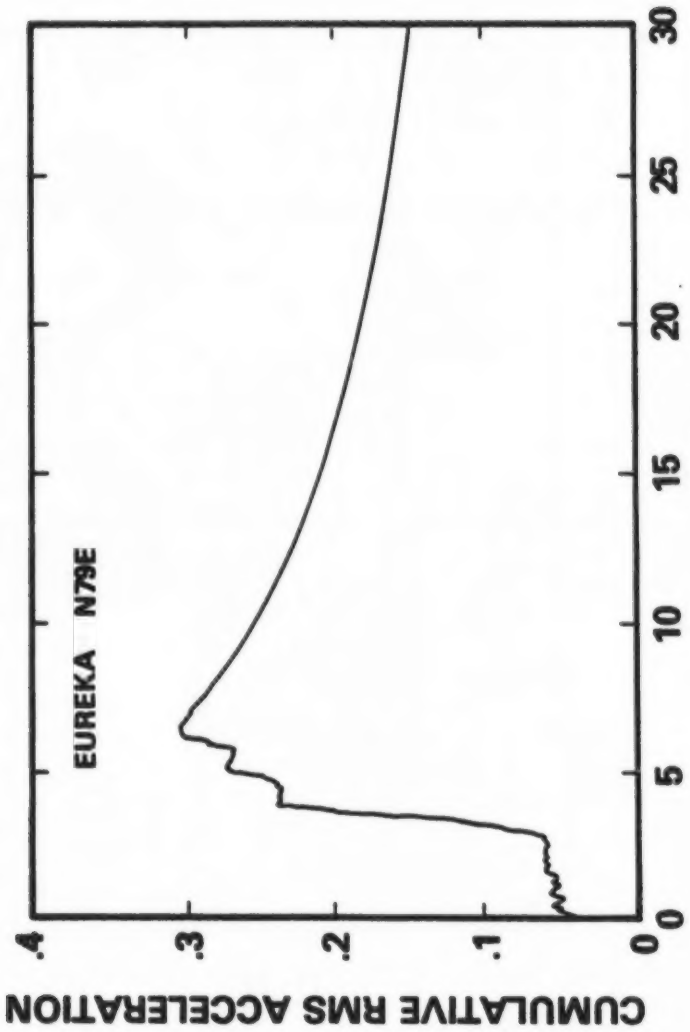


FIG. 5.1 TYPICAL CUMULATIVE RMS FUNCTION - SEISMIC GROUND MOTION

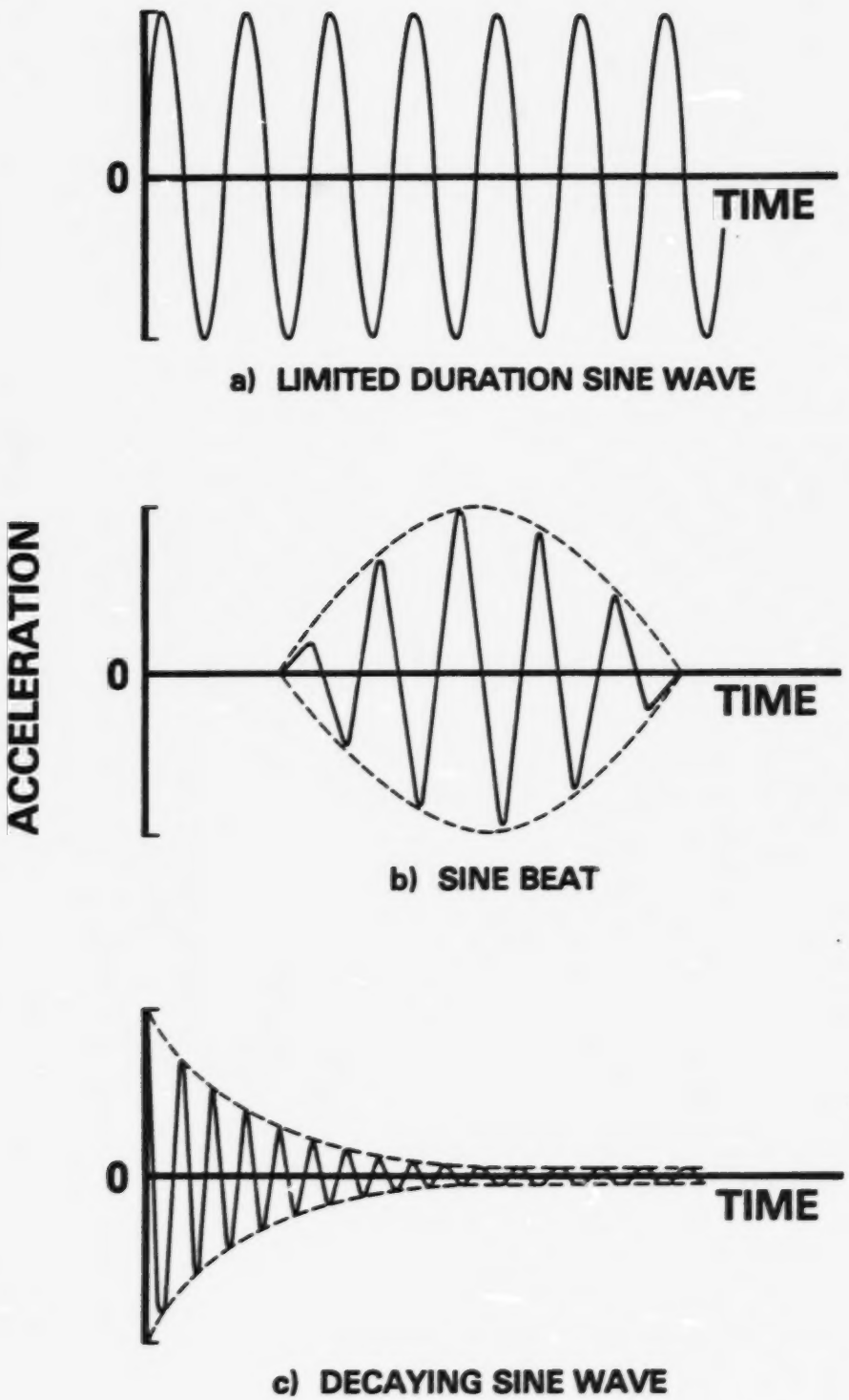


FIG. 5.2 SINGLE FREQUENCY MOTIONS

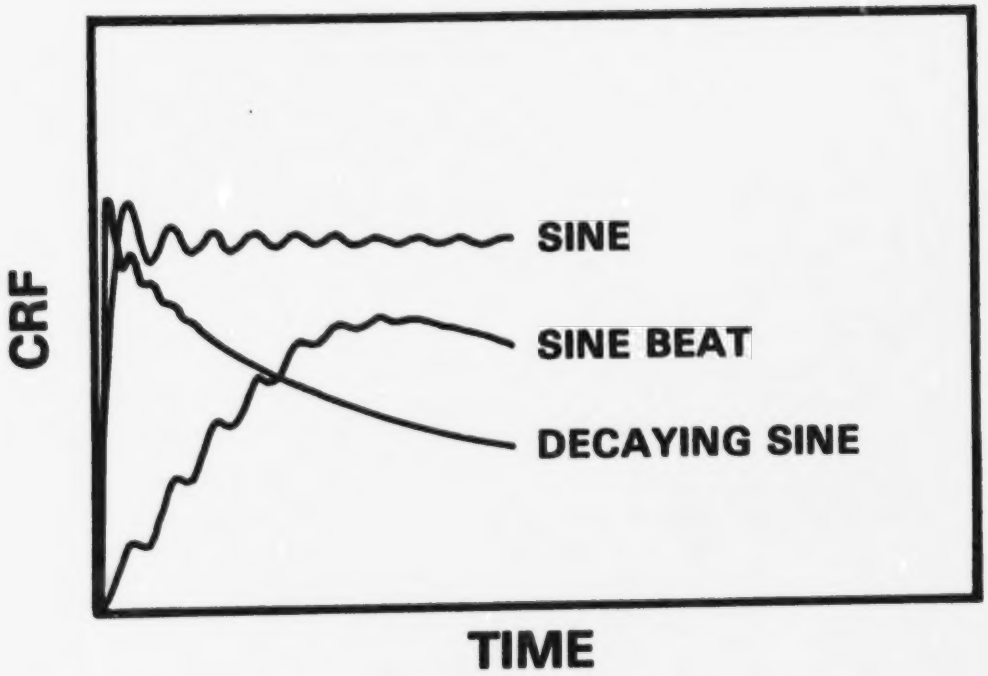


FIG. 5.3 **CUMULATIVE RMS FUNCTIONS OF SINGLE FREQUENCY MOTIONS**

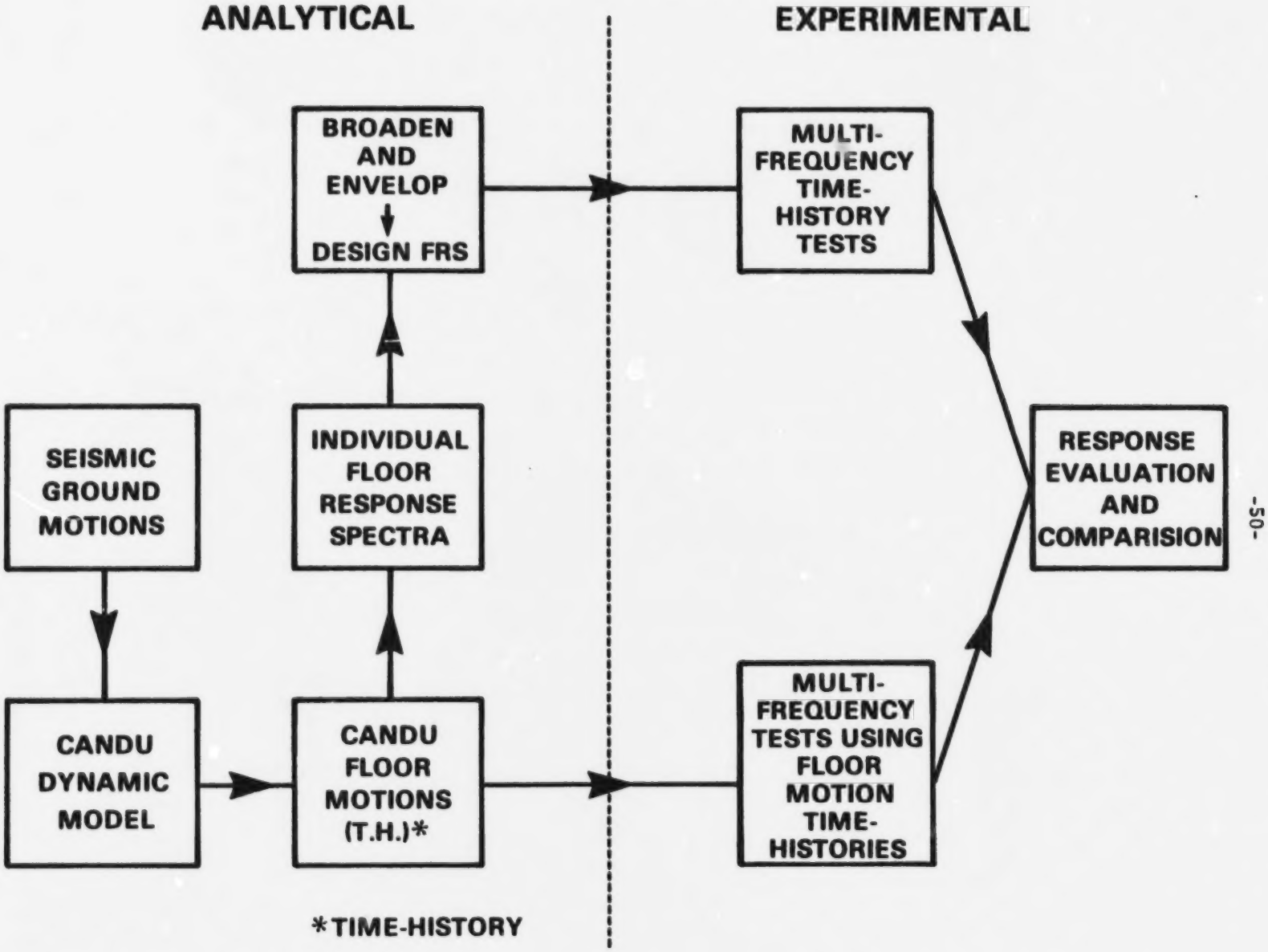


FIG. 5.4 **SCHEMATIC OUTLINE OF TEST PROCEDURE**

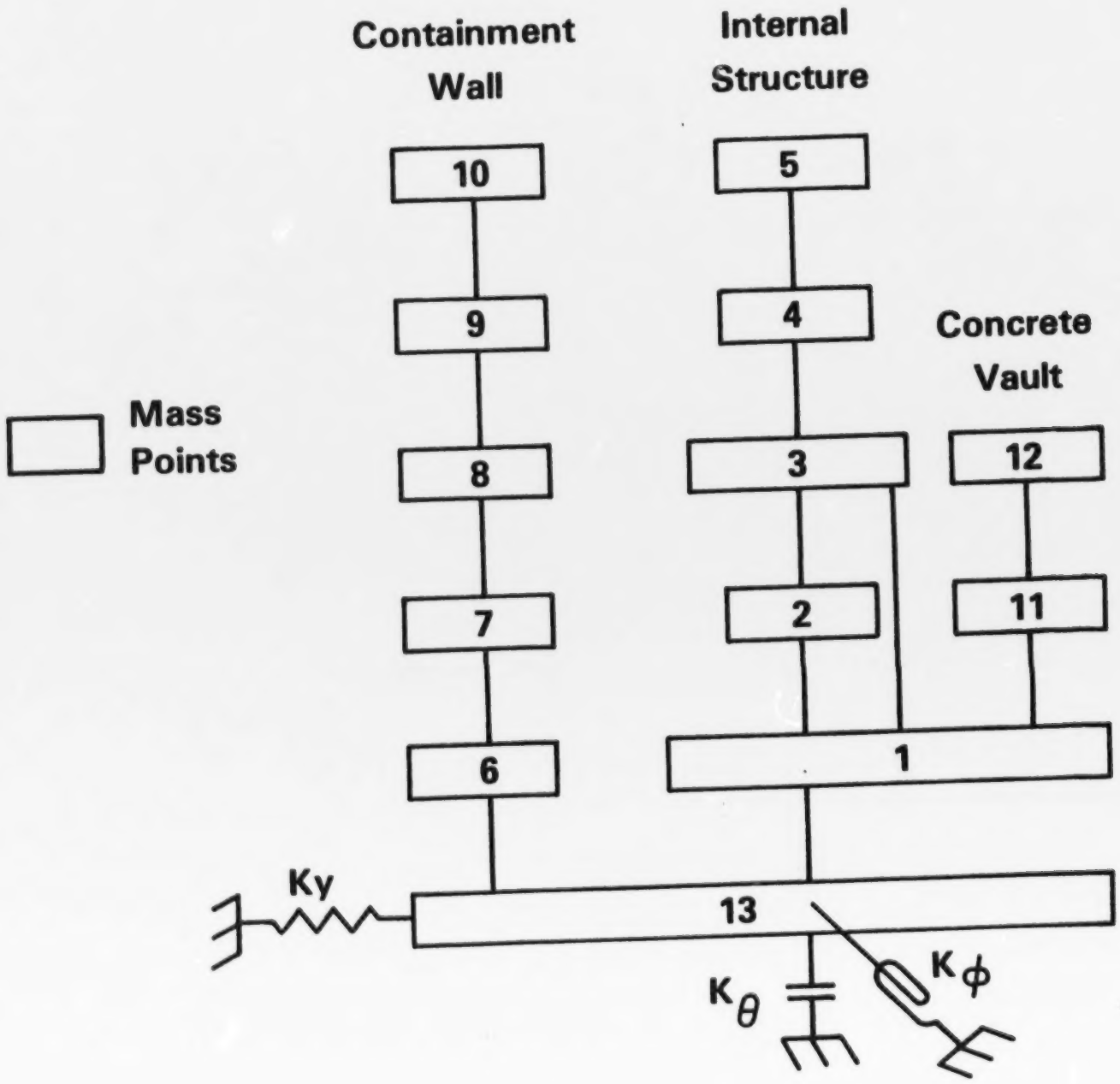


FIG. 5.5 DYNAMIC MODEL OF CANDU REACTOR

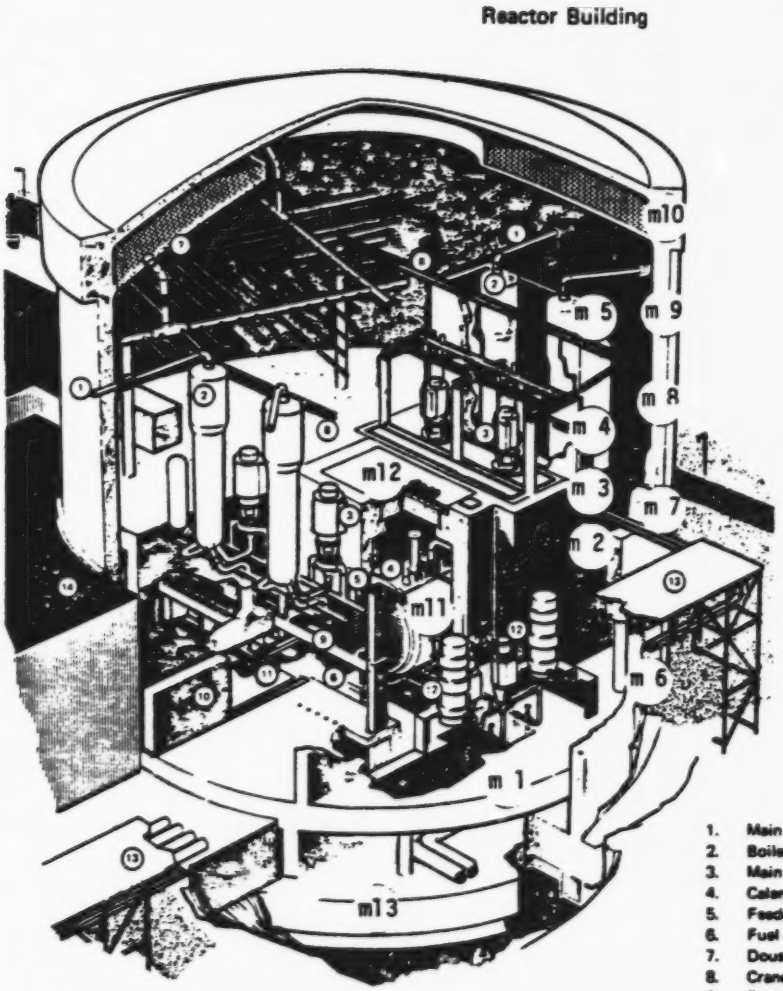


FIG. 5.6 LOCATION OF DYNAMIC MODEL MASSES IN CANDU REACTOR BUILDING

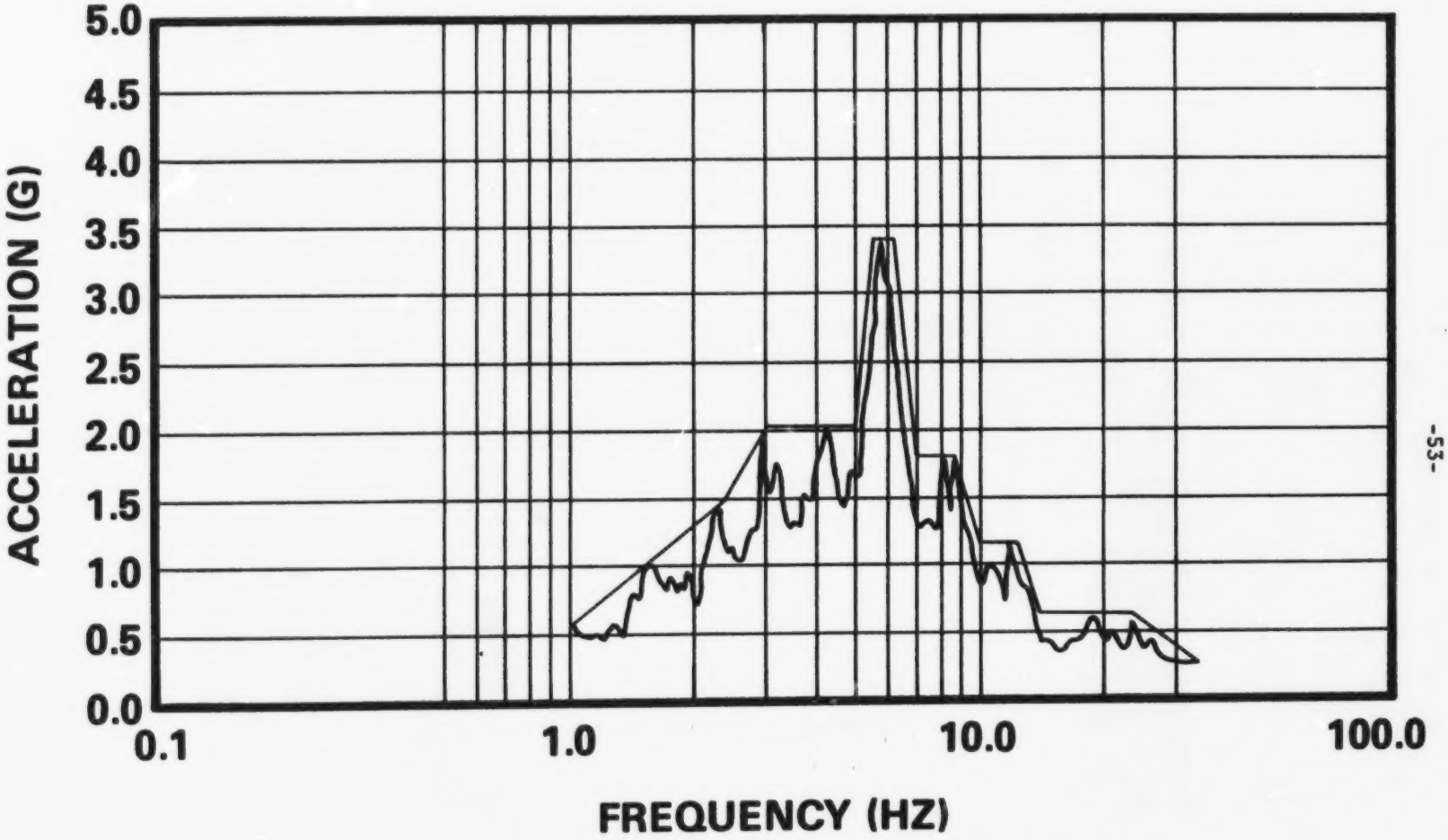


FIG. 5.7 TYPICAL ENVELOPE AND DESIGN RESPONSE SPECTRA (LEVEL 12, 1% DAMPING)

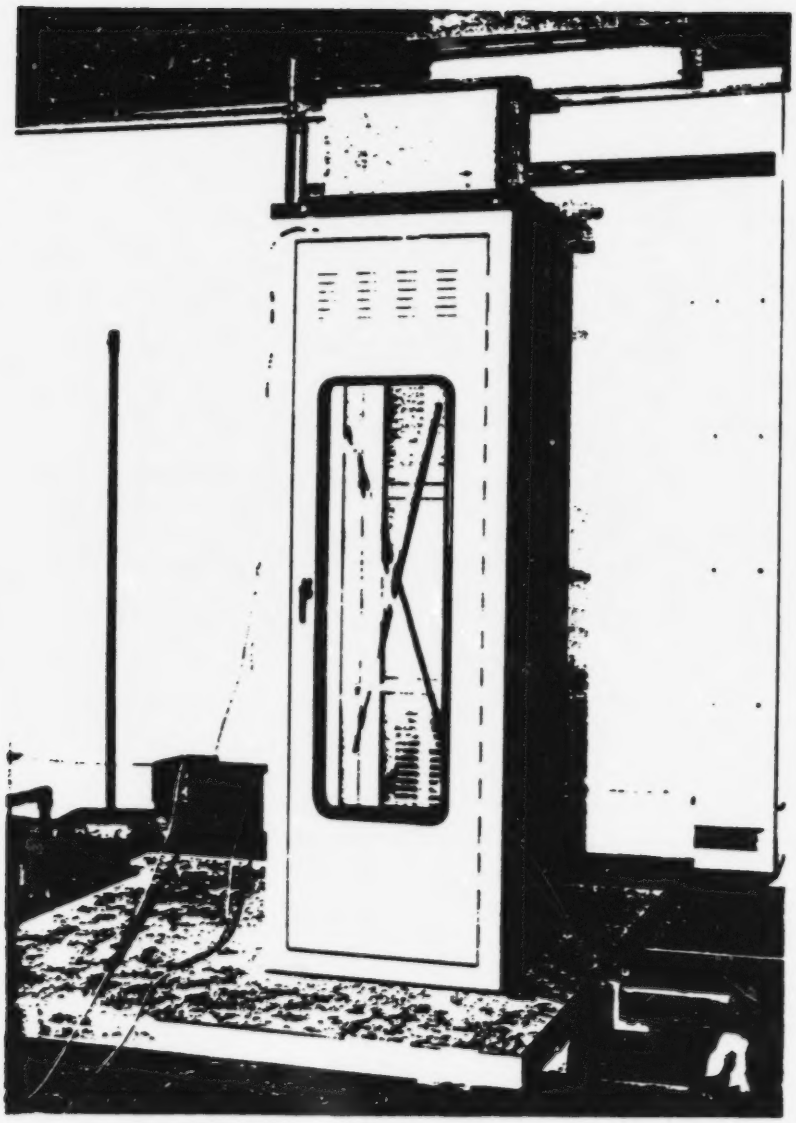


FIG. 5.8 PHOTOGRAPH OF INSTRUMENT CABINET

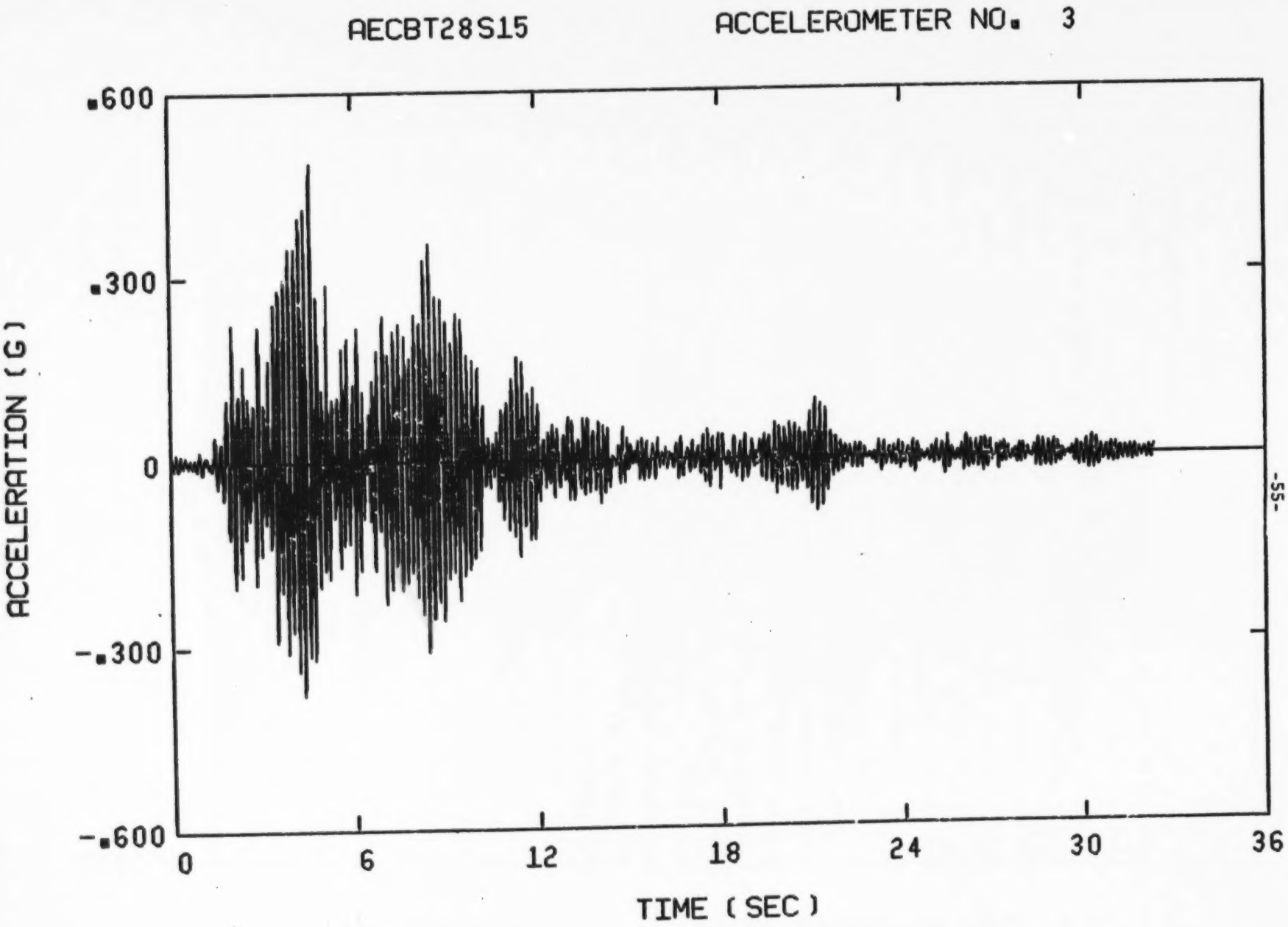


FIG. 5.9(a) TYPICAL INSTRUMENT CABINET RESPONSE TIME HISTORY

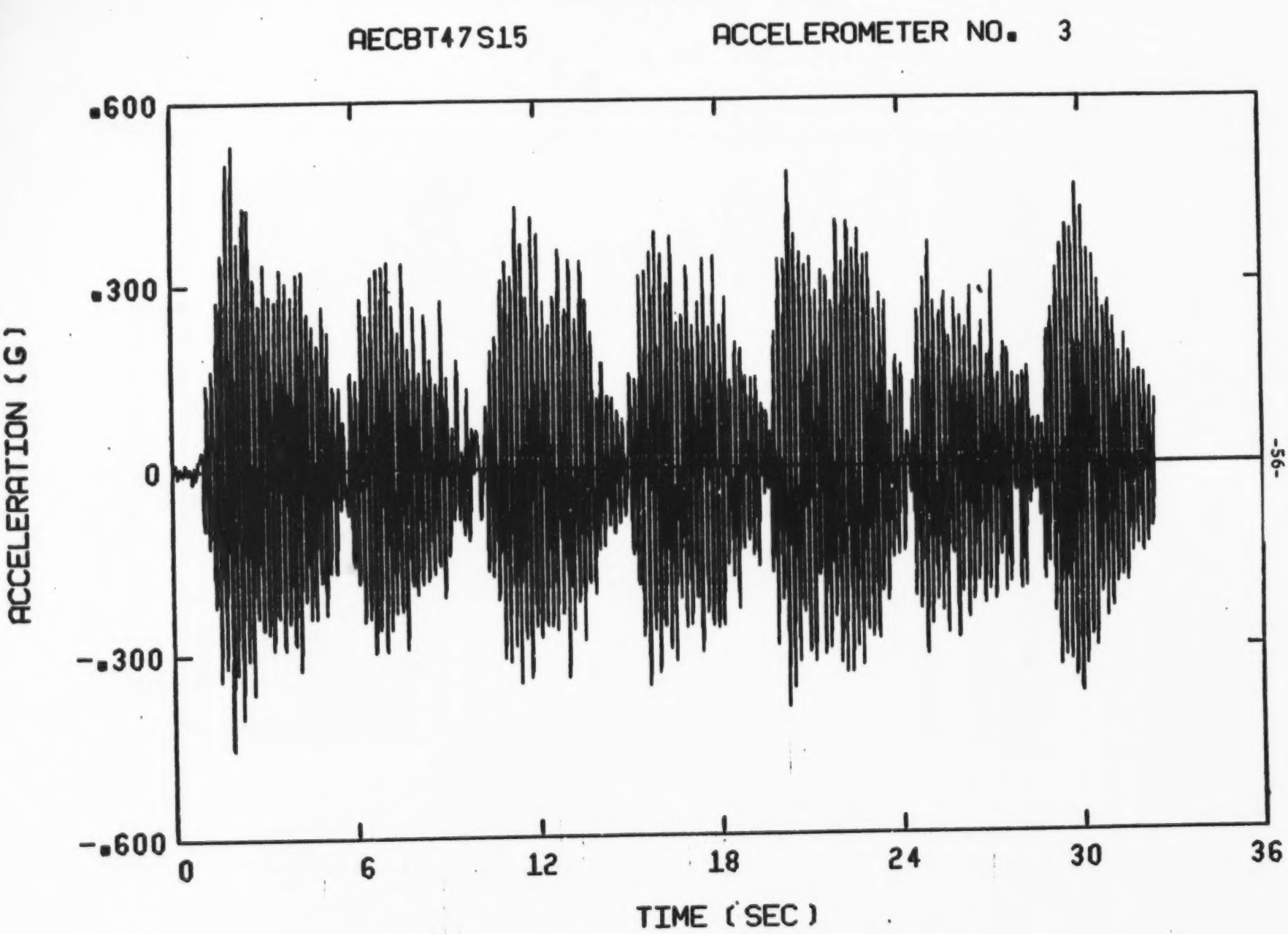


FIG. 5.9(b) TYPICAL INSTRUMENT CABINET RESPONSE TIME HISTORY

6. SUMMARY AND CONCLUSIONS

The general objectives of the study described in this report were to review the seismic qualification of equipment in the CANDU reactor, including such aspects as evaluating current requirements, developing a methodology for system qualification, and evaluating analysis and testing procedures. A fault tree study was used to evaluate current seismic qualification requirements; a logic diagram identified the various paths of failure necessary to result in public release of radioactivity following an earthquake. By comparing the systems involved along each failure path with the design requirements, it was found that the nuclear power plant as a whole would be seismically qualified if the specified design requirements for each system were met.

Based on the foregoing, it is clear that the adequacy of the overall nuclear power plant depends upon the adequacy of the seismic qualification of the different systems which are designed to ensure the safety of the plant. When evaluating "safety systems", it was determined that the seismic qualification of components or individual pieces of equipment within those systems is a necessary but insufficient condition to ensure the qualification of the overall safety system. The additional requirements, over and above component qualification, were then specified in terms of two additional types of qualification, namely location qualification and interface qualification.

In terms of component qualification, a critical evaluation of current seismic qualification procedures was included in this study. The two most common approaches are qualification by analysis and by testing, each of which has its advantages and drawbacks. The primary advantage of analysis is its inherent flexibility for use in qualifying a wide variety of equipment, irrespective of shape, size or weight. If carried out properly, analysis is a viable approach for ensuring the integrity of equipment after an earthquake. On the other hand, qualification by testing has the advantage of being able to demonstrate functionality in a direct manner. Testing is limited by the shaking capacity of available testing facilities and would not be suitable for equipment of large size and/or weight. The emphasis of the evaluation in this study was on the comparison of the two different approaches and on the comparison of methods and procedures within each approach.

Because of the difficulty in comparing test procedures, these were subject to additional investigations. An important aspect of this study was the development of a number of "new" parameters which would provide a more complete characterization of seismic floor motions. Single frequency testing procedures were evaluated using these characterization parameters with the result that the sine beat test was found to provide the best simulation (within the single frequency test procedures) of actual seismic floor motions. Multi-frequency test procedures were then evaluated by testing an actual instrument cabinet.

The authors conclude this report by presenting some general observations and conclusions concerning the "state of the art" of seismic qualification of equipment, as it is being done in Canada at the present time. The general level and framework of seismic qualification is certainly satisfactory. It is likely that there is considerable conservatism in the testing procedures presently being used but it would be difficult to provide an analytical assessment of the degree of conservatism which might be involved. Lack of knowledge concerning the characteristics of seismic floor motions has resulted in procedures which likely over-compensate for that shortcoming. While this might be viewed as providing additional protection, it should be noted that it does add to the cost of the facility and may detract from achieving the best design for normal operating conditions.

As mentioned in the body of this report, more attention should be paid to the overall system qualification of seismic safety systems, particularly concerning those aspects which interface physically with other non-qualified equipment. This aspect can probably be done best by instituting careful inspection rather than by attempting to devise more comprehensive analytical or testing procedures.

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